Dual- and Multi-Energy CT
Physical Background and Concepts

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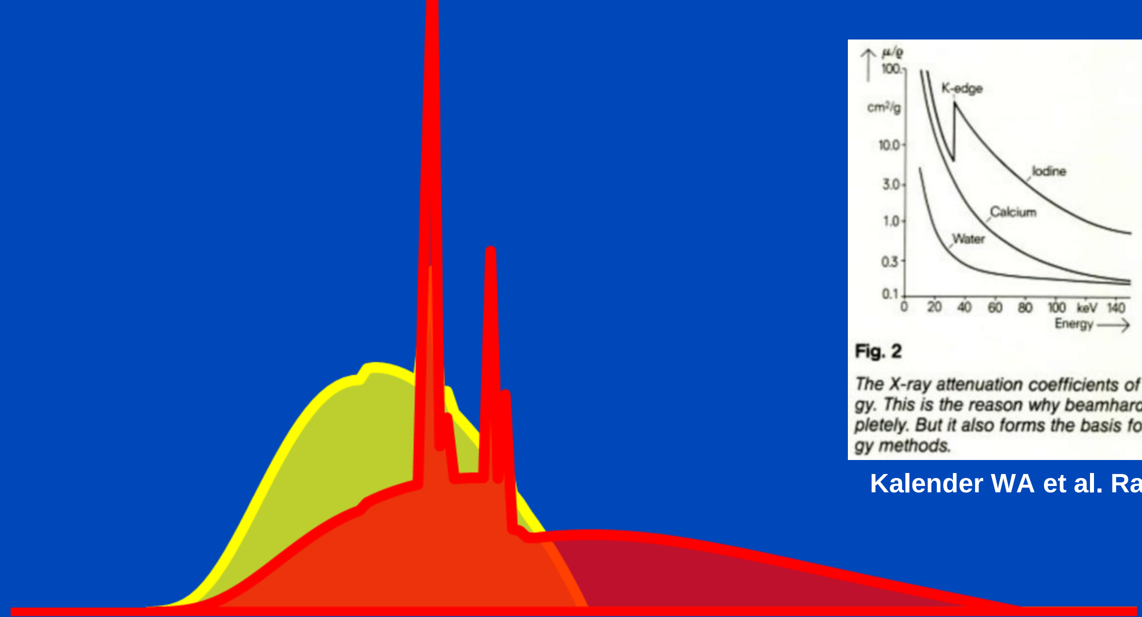
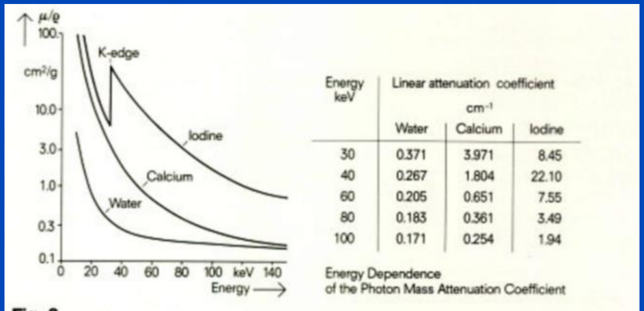
DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Clarification of Terminology

- **Dual energy CT (DECT)**
  - Simultaneous measurement with two different detected spectra
  - Various different technical realizations
- **Multi energy CT (MECT)**
  - Simultaneous measurement with three or more detected spectra
  - Currently only realized in (experimental) photon counting CT
- **Spectral CT**
  - CT exploiting the different x-ray spectral behaviour of materials
  - Everything above, i.e. DECT and MECT
- **Energy-integrating or conventional CT**
  - CT with conventional indirectly converting detectors
  - Can realize DECT
- **Photon-counting CT**
  - CT with novel directly converting energy-selective detectors
  - Can realize DECT and MECT

Emitted spectrum = x-ray spectrum as it leaves the x-ray source and prefilters
Detected spectrum = x-ray spectrum as it is seen by the detector





Energy keV	Linear attenuation coefficient cm⁻¹ Water	Calcium	Iodine
30	0.371	3.971	8.45
40	0.267	1.804	22.10
60	0.205	0.651	7.55
80	0.183	0.361	3.49
100	0.171	0.254	1.94

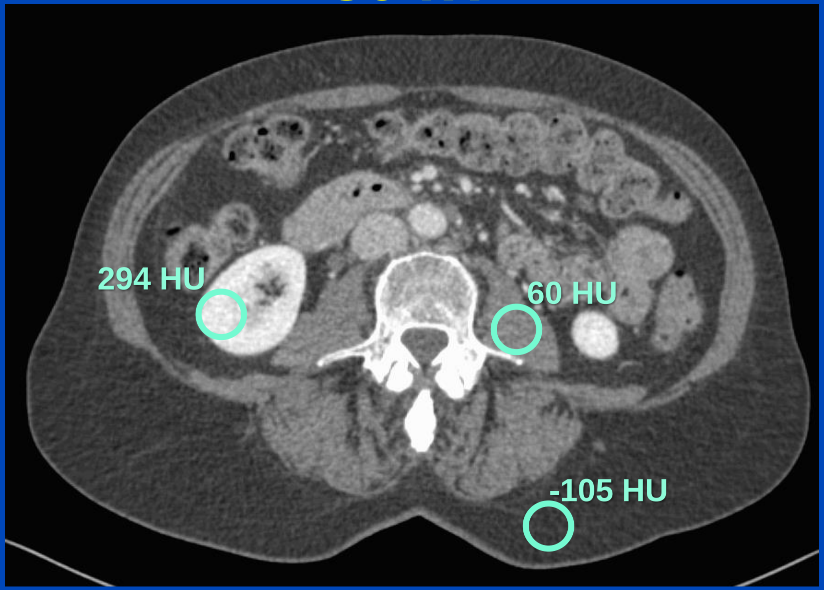
Energy Dependence
of the Photon Mass Attenuation Coefficient

Fig. 2

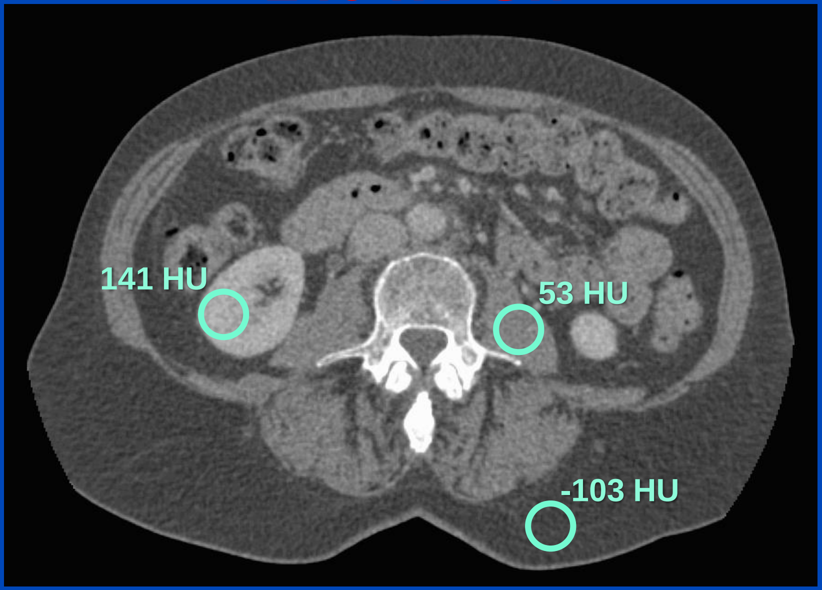
The X-ray attenuation coefficients of different materials vary widely with energy. This is the reason why beamhardening effects cannot be controlled completely. But it also forms the basis for material-selective imaging by dual energy methods.

Kalender WA et al. Radiology 164:419-423, 1987

80 kV



140 kV Sn



***C* = 50 HU, *W* = 600 HU**

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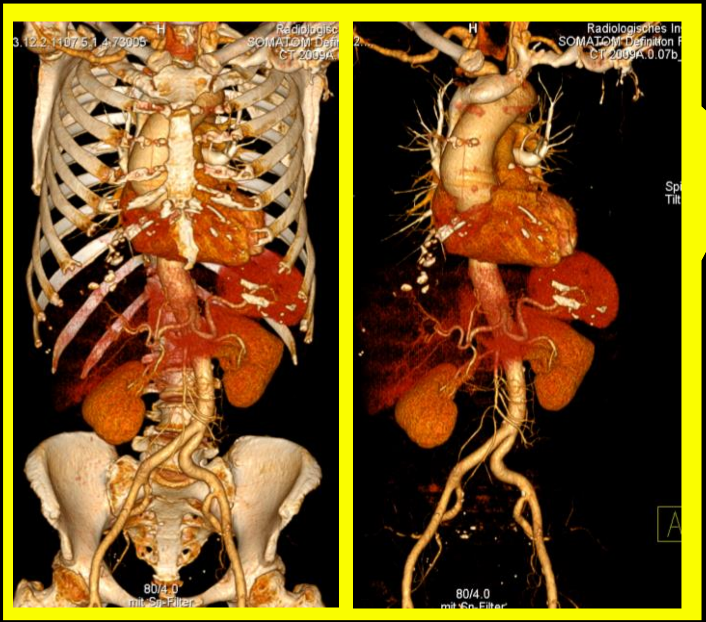
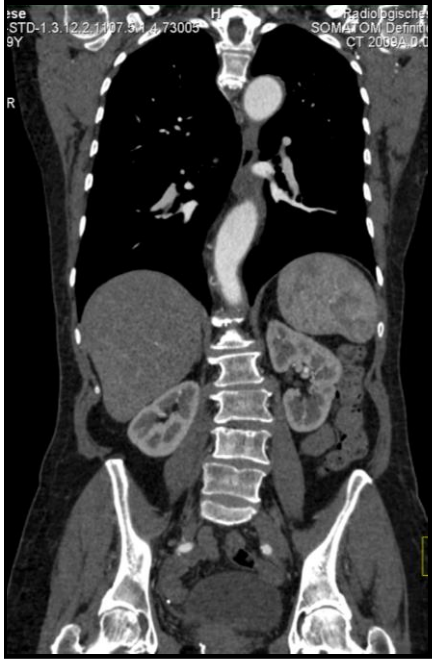
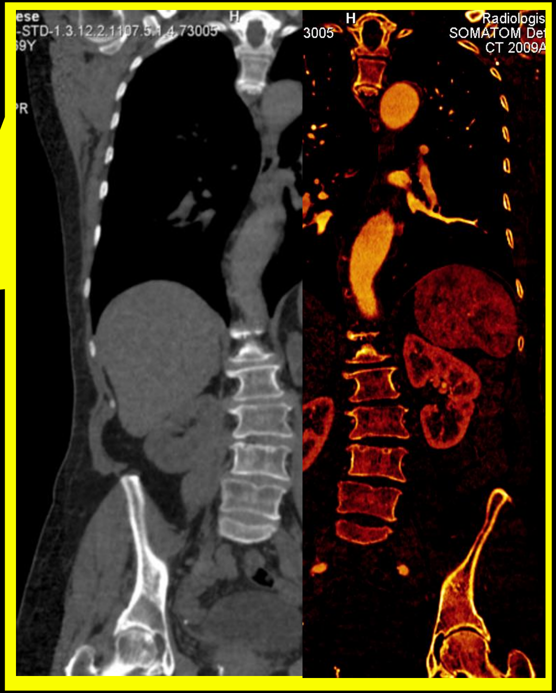
DE bone removal



Single DECT scan





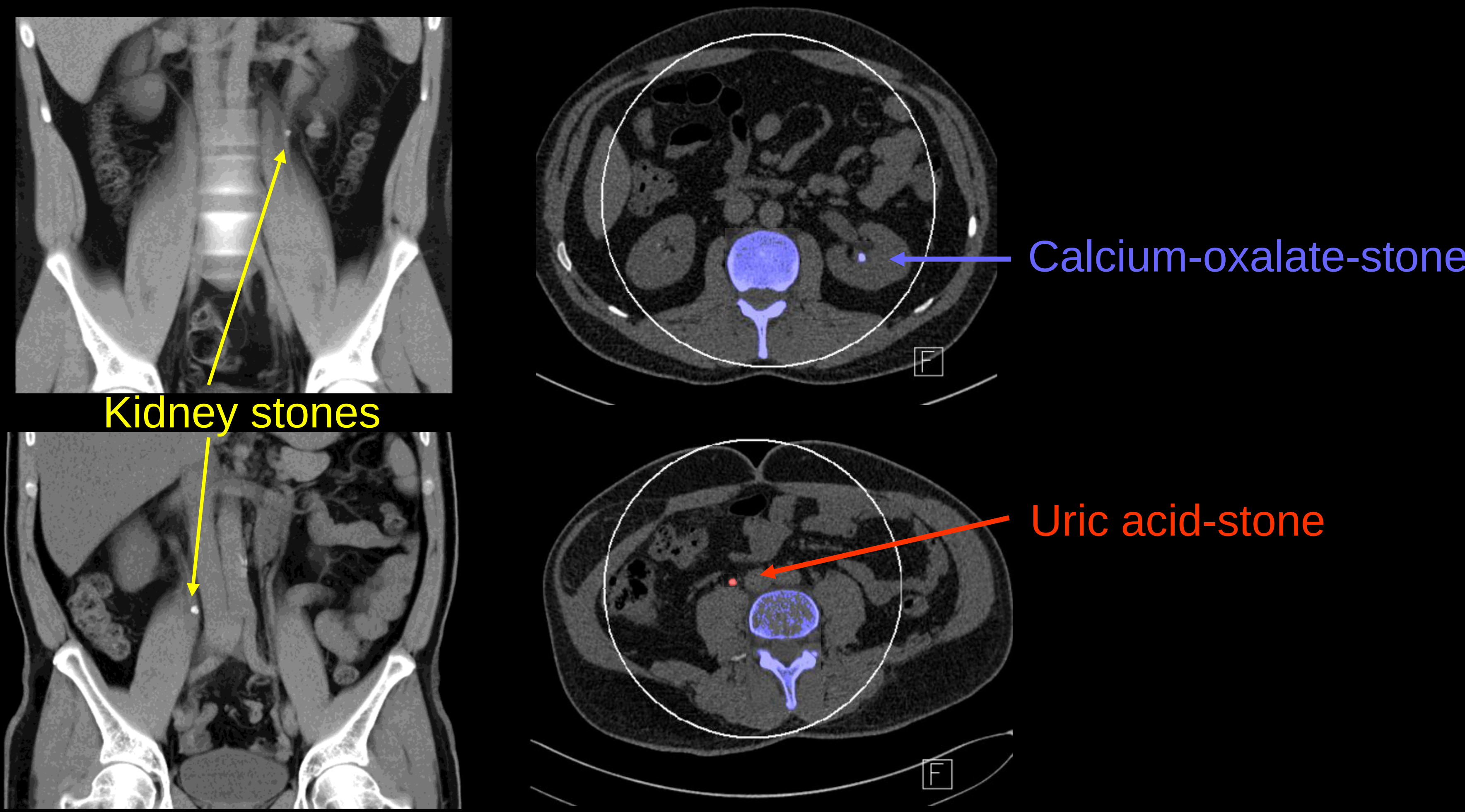
Virtual non-contrast and iodine image

Dual Energy whole body CTA: 100/140 Sn kV @ 0.6 mm

Courtesy of Friedrich-Alexander University Erlangen-Nürnberg

“Spectroscopy“: more specific tissue characterization

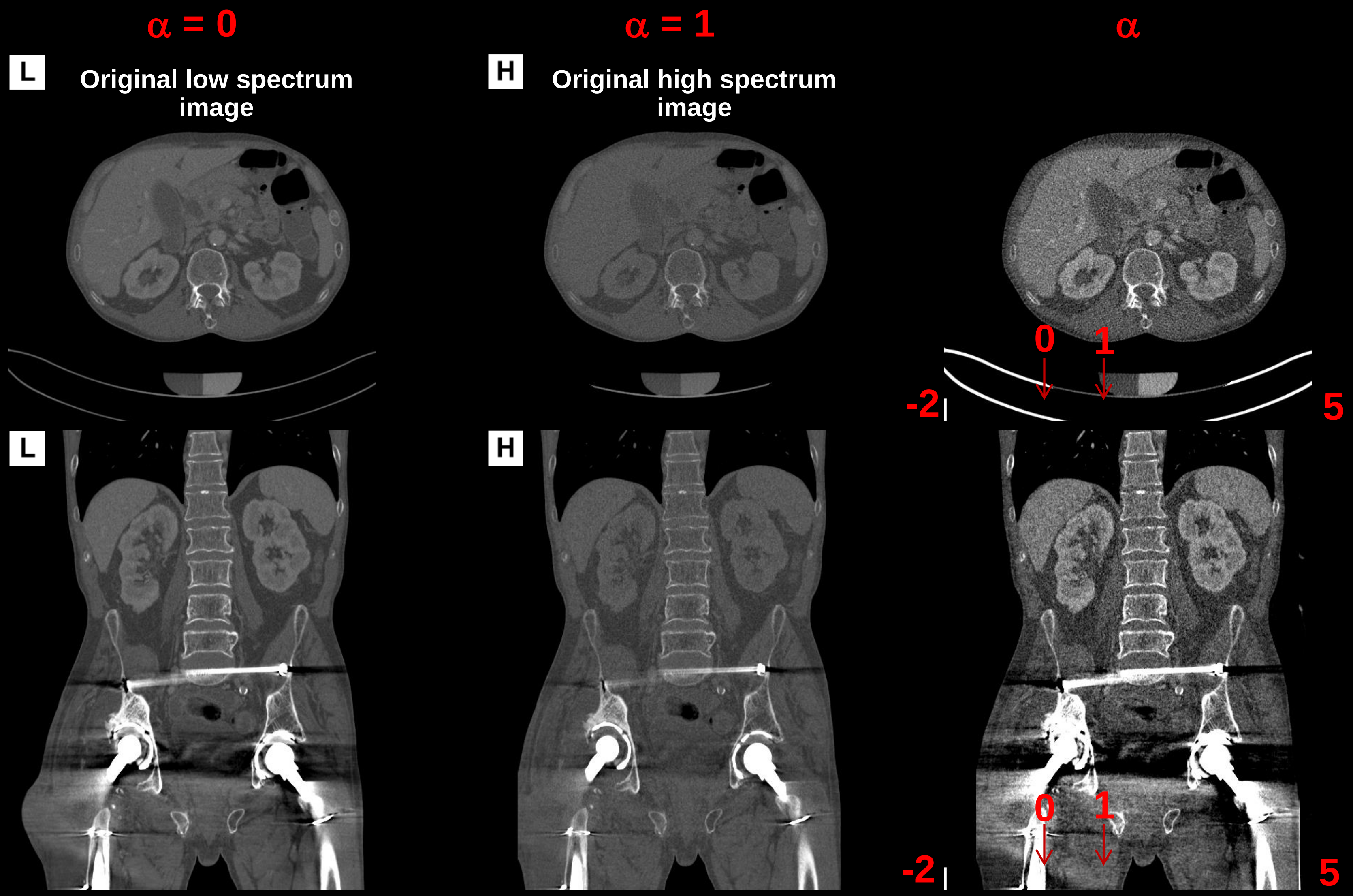
→ Detection and visualization of calcium, iron, uric acid, …..



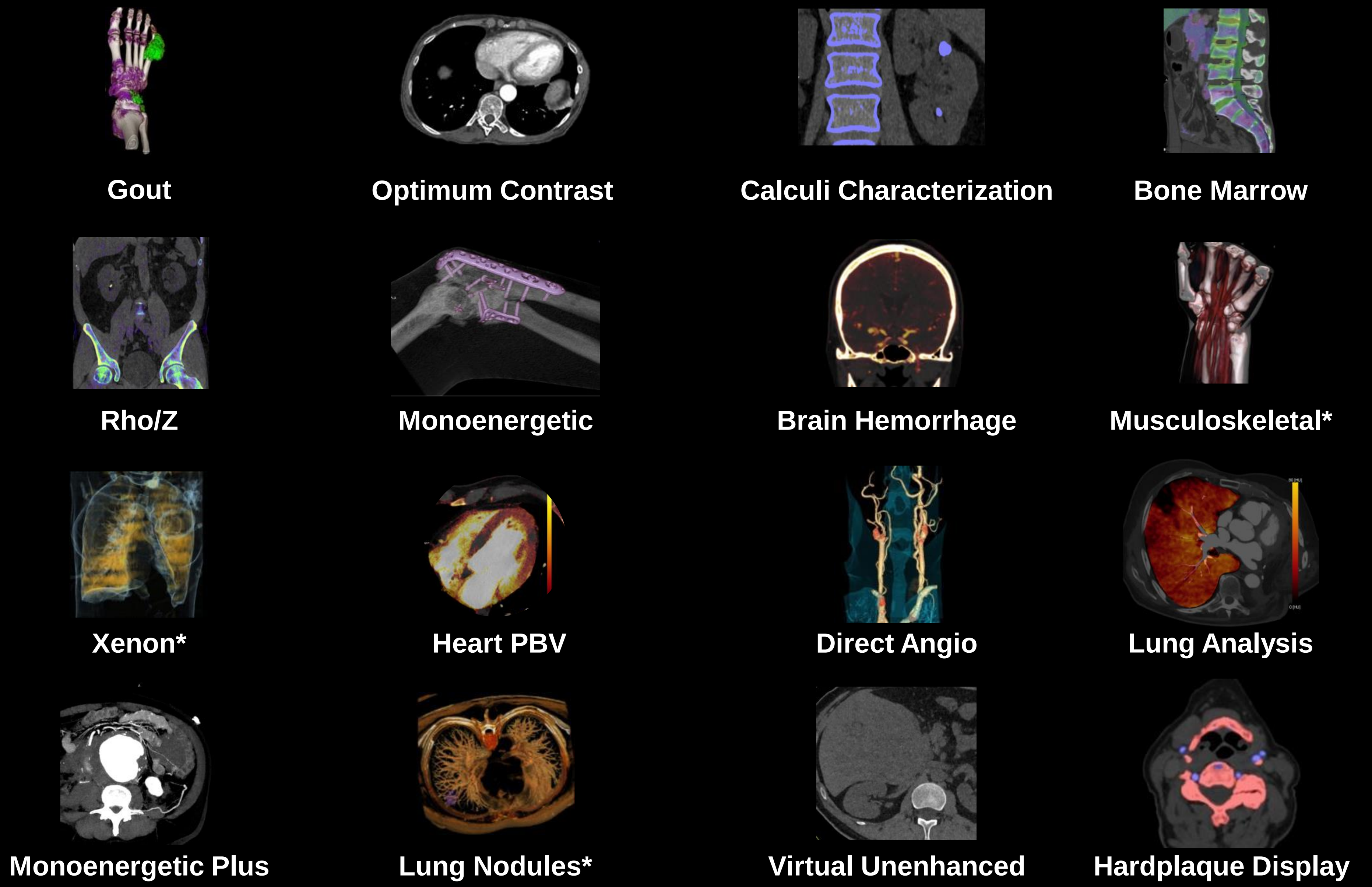
Courtesy of Klinikum Großhadern, LMU München

Linear Mixing

$$f_\alpha = (1-\alpha)\, f_{\mathrm{L}} + \alpha\, f_{\mathrm{H}}$$



C = 300 HU, *W* = 1400 HU



Syngo.CT DECT application examples. Virtual unenhanced contains liver VNC, lung analysis contains lung PBV.
Courtesy of Siemens Healthineers, Forchheim, Germany

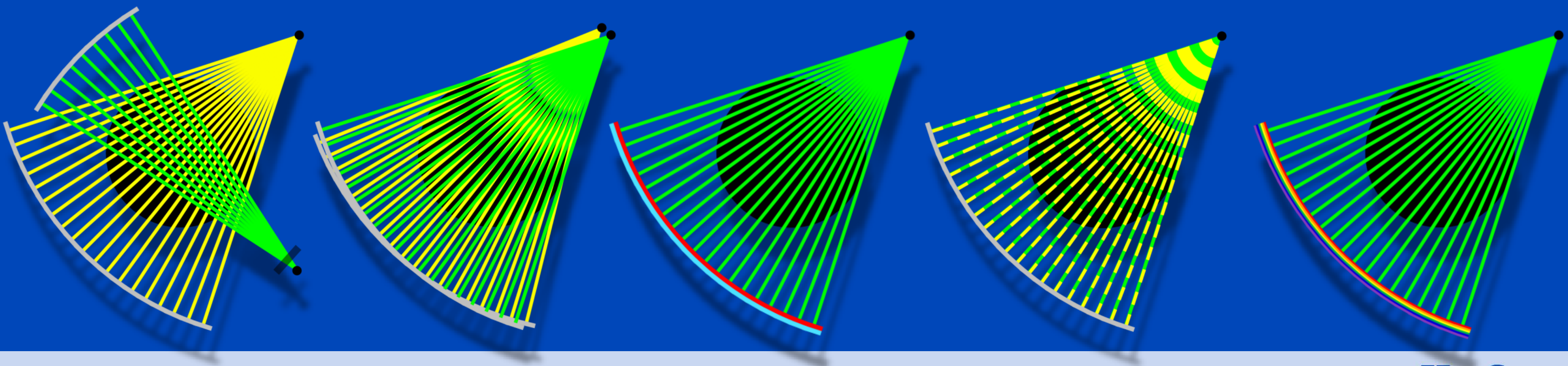
DECT Technology

- **In the clinic:**

– Multiple scans at different spectra	mid-range
– Dual source CT (DSCT), generations 2, and 3	high-end
– Fast tube voltage switching	high-end
– Dual layer sandwich detectors	high-end
– Split filter	mid-range

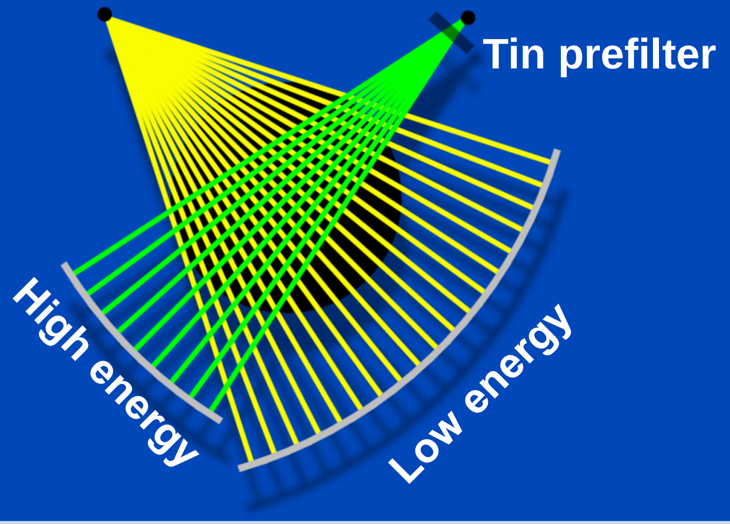
- **First prototypes:**

– Photon counting detectors (two or more energy bins)	high-end



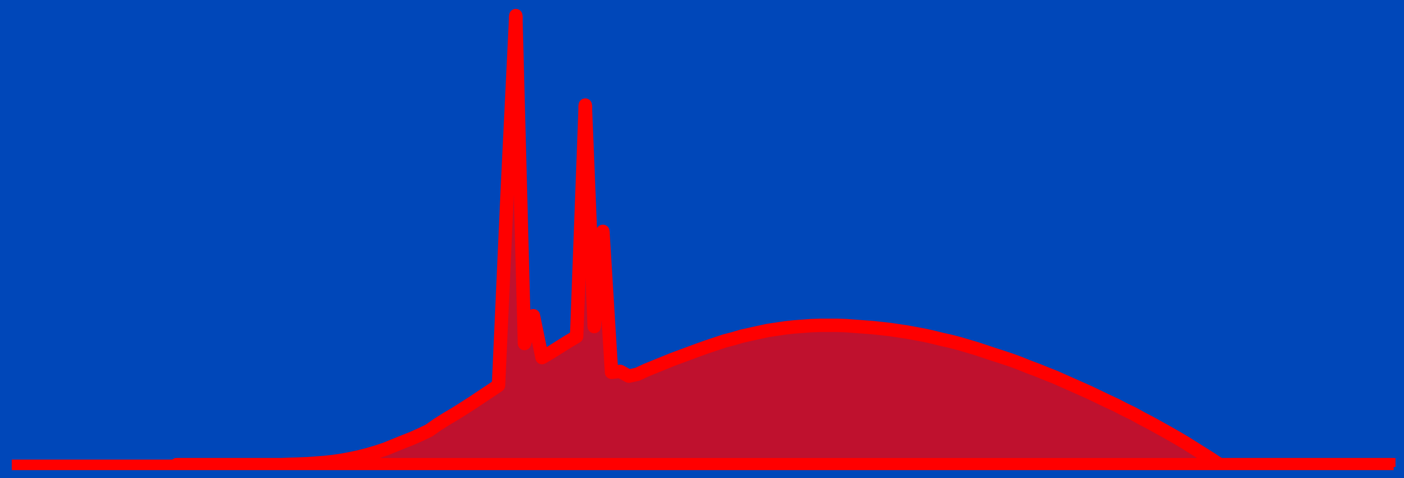
DECT Technology

- DECT approaches in the clinic:
  - Dual source DECT (Siemens)



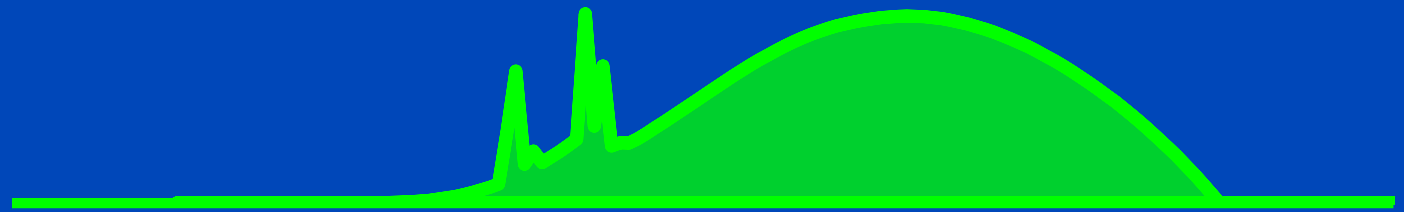
Siemens Somatom Force

Effect of the Prefilter: Without Sn



Spectra as seen after having passed a 32 cm water layer.

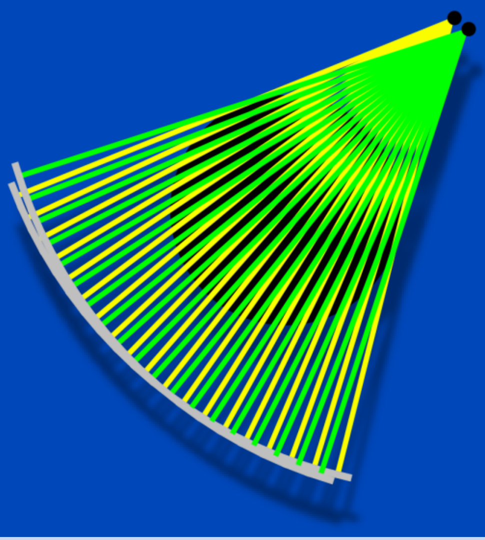
Effect of the Prefilter: With 0.4 mm Sn

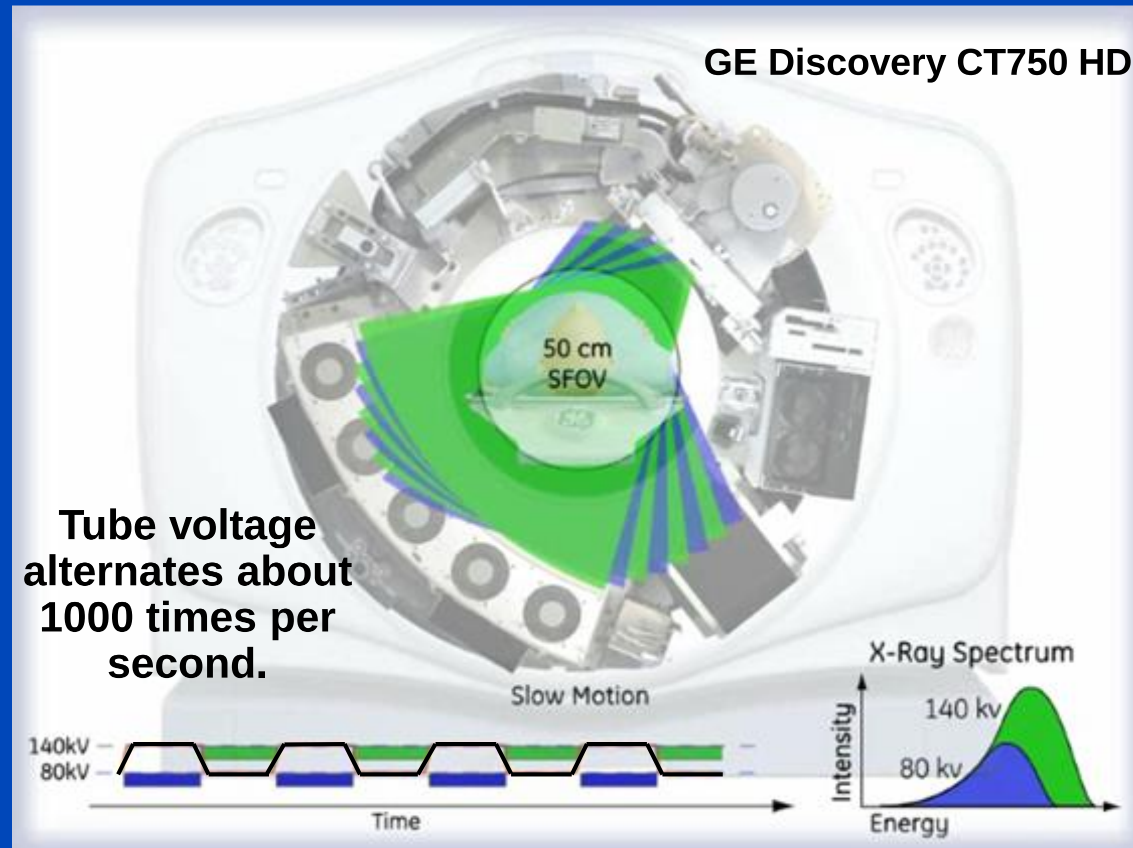


Spectra as seen after having passed a 32 cm water layer.

DECT Technology

- DECT approaches in the clinic:
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)





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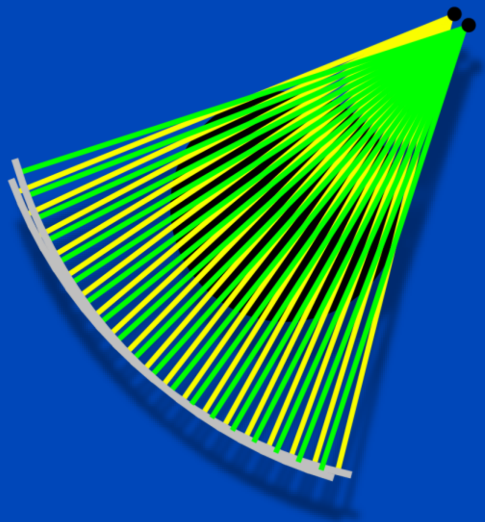

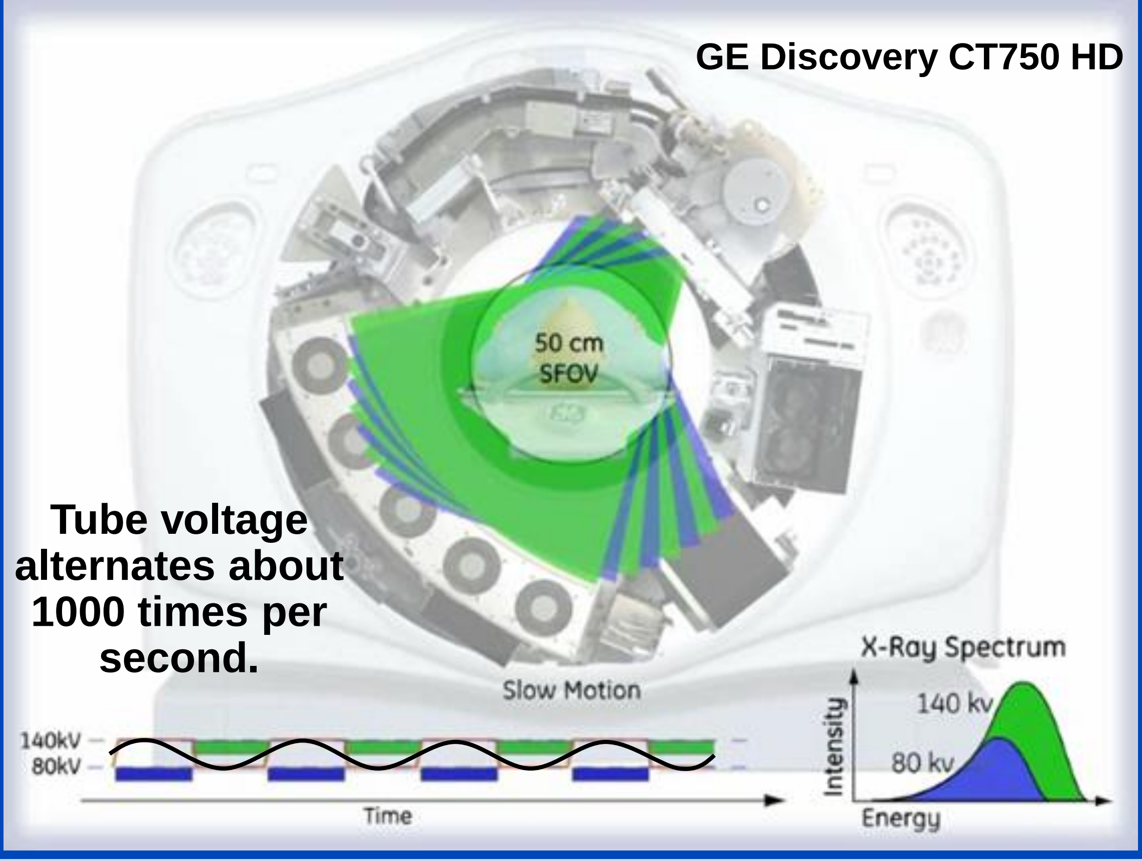

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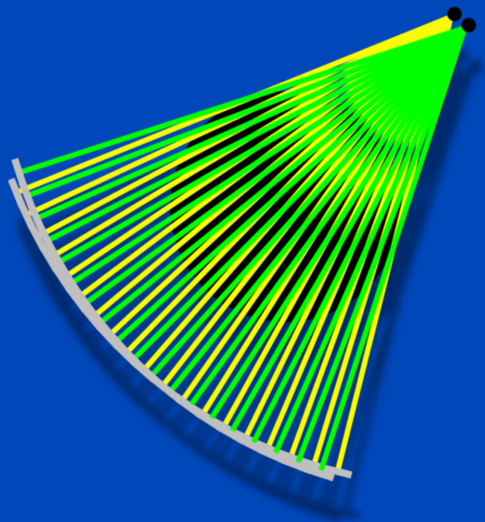

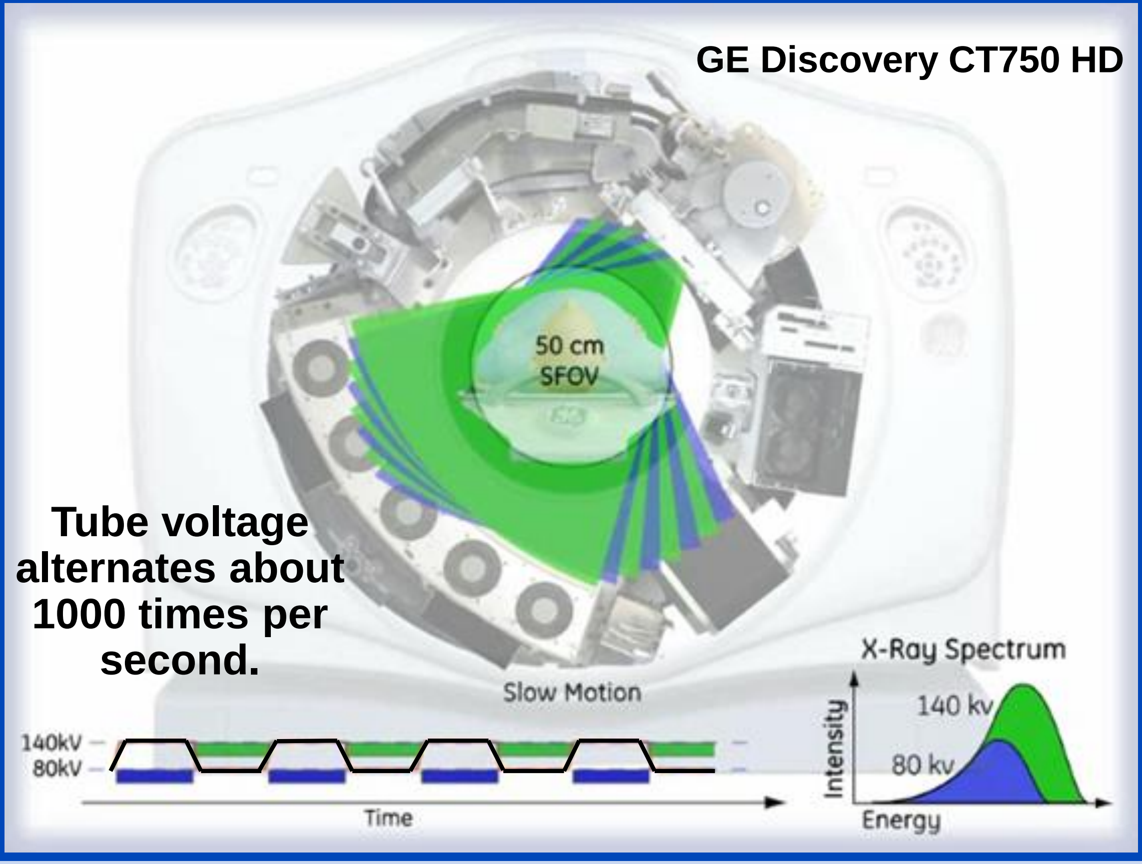

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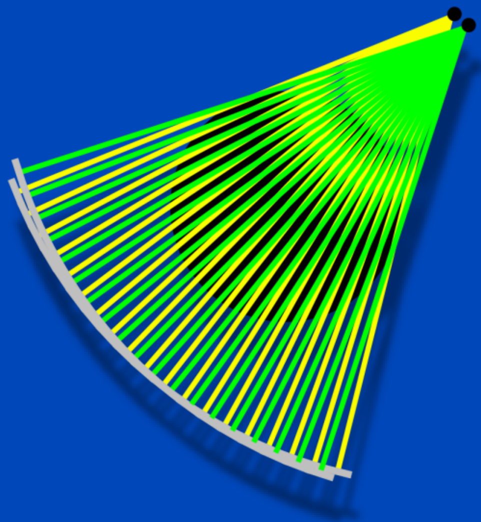
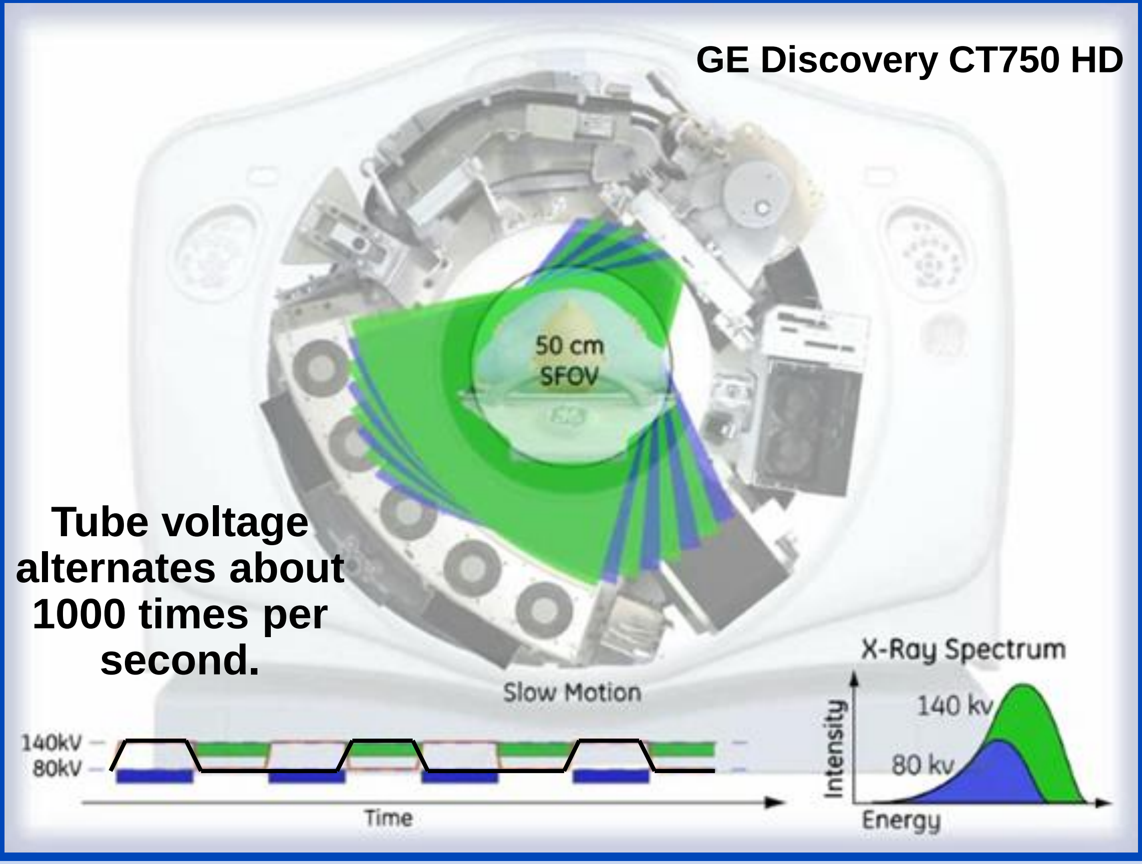
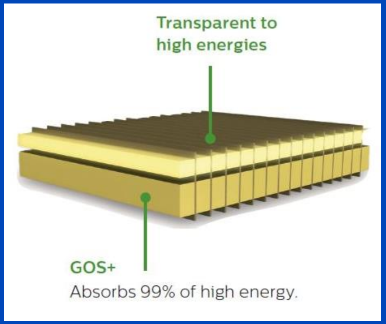
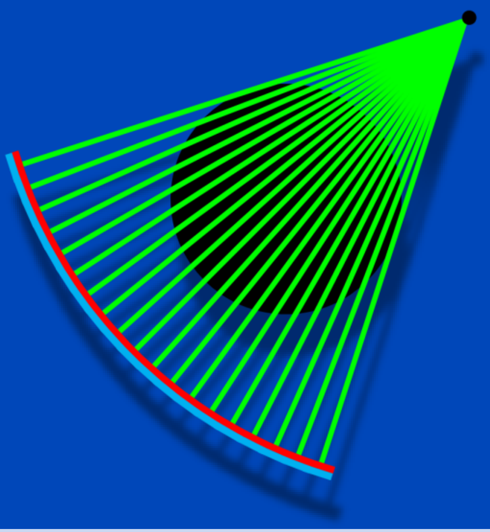


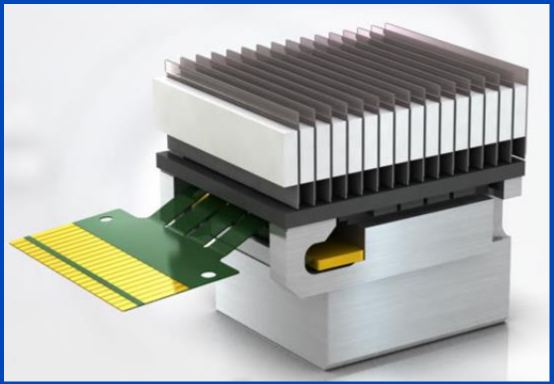


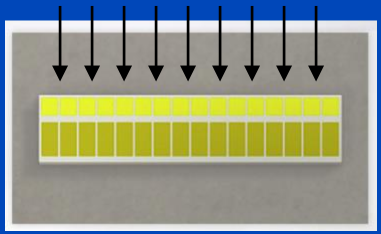
DECT Technology



- **DECT approaches in the clinic:**
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)
  - Dual layer (sandwich) detector (Philips)





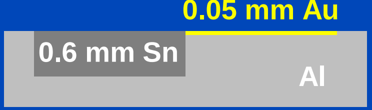


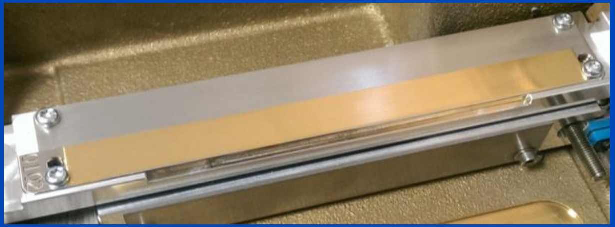
Top layer acts as a prefilter
for the bottom layer.

Philips IQon

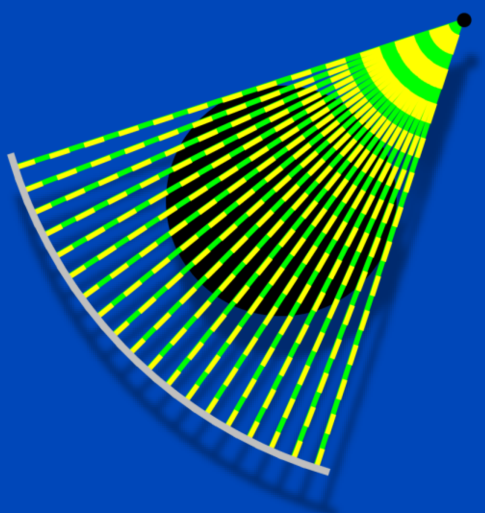
Siemens X.Cite: 0.7 mm Sn and 0.07 mm Au

DECT Technology

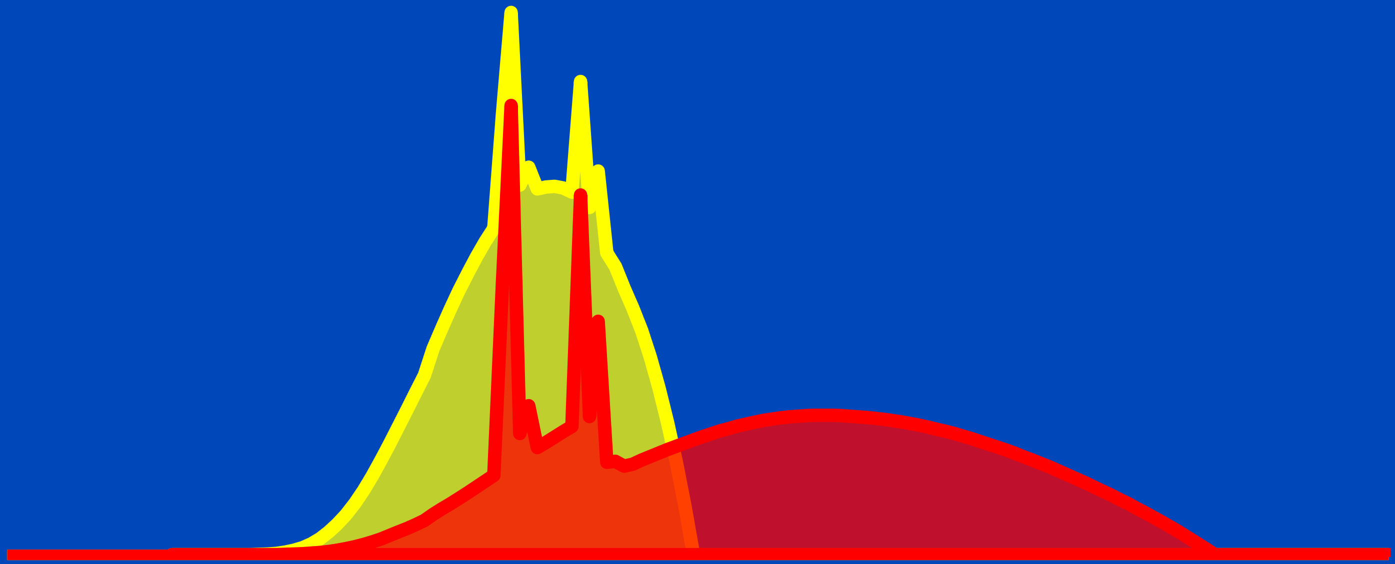




- **DECT approaches in the clinic:**
  - Dual source DECT (Siemens)
  - Fast tube voltage switching (GE)
  - Dual layer (sandwich) detector (Philips)
  - Split filter (Siemens)

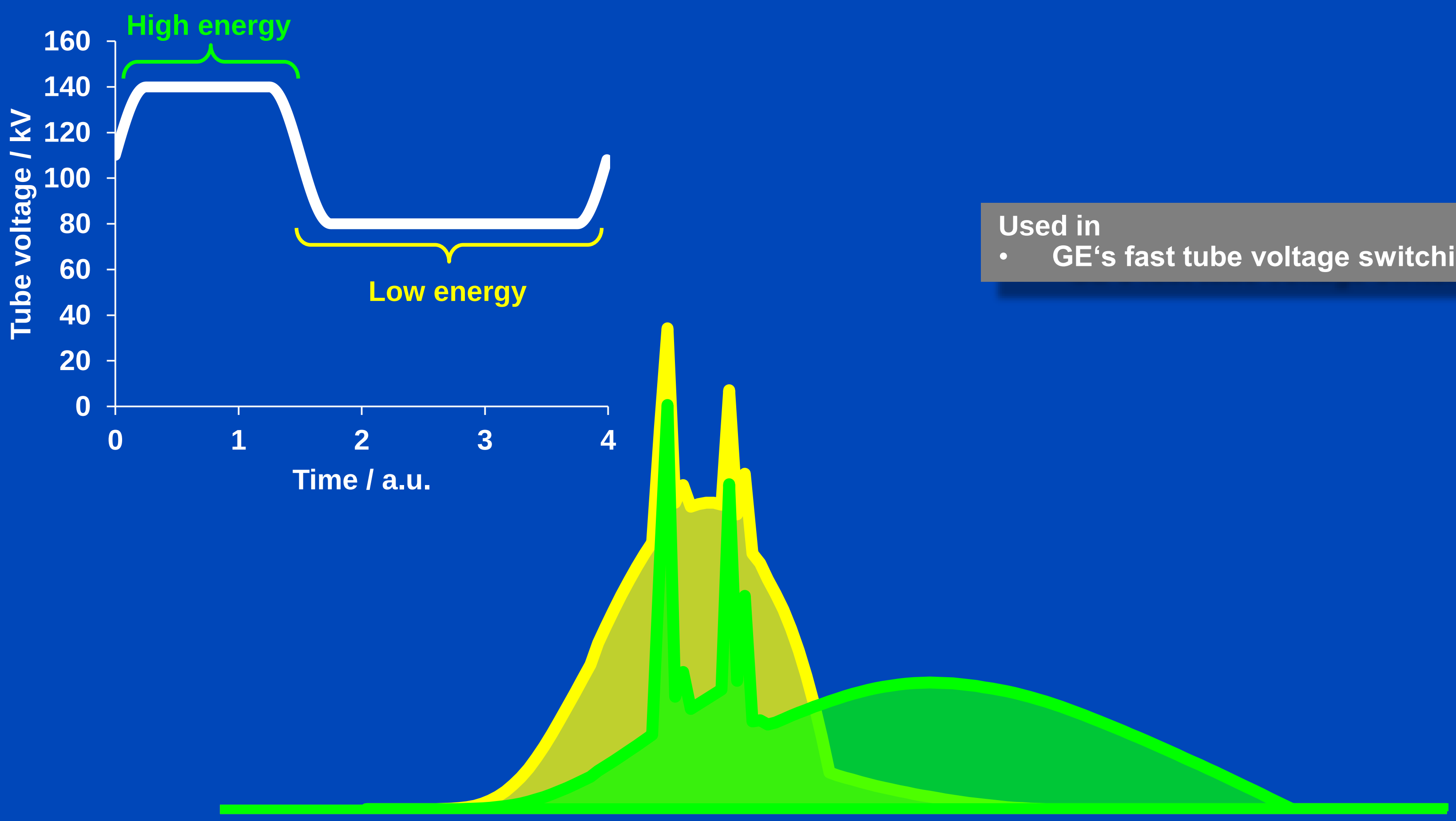


80 kV / 140 kV



Used in
- **Siemens' 1st generation DSCT**

80 kV / 140 kV Sinrect kV-Switching

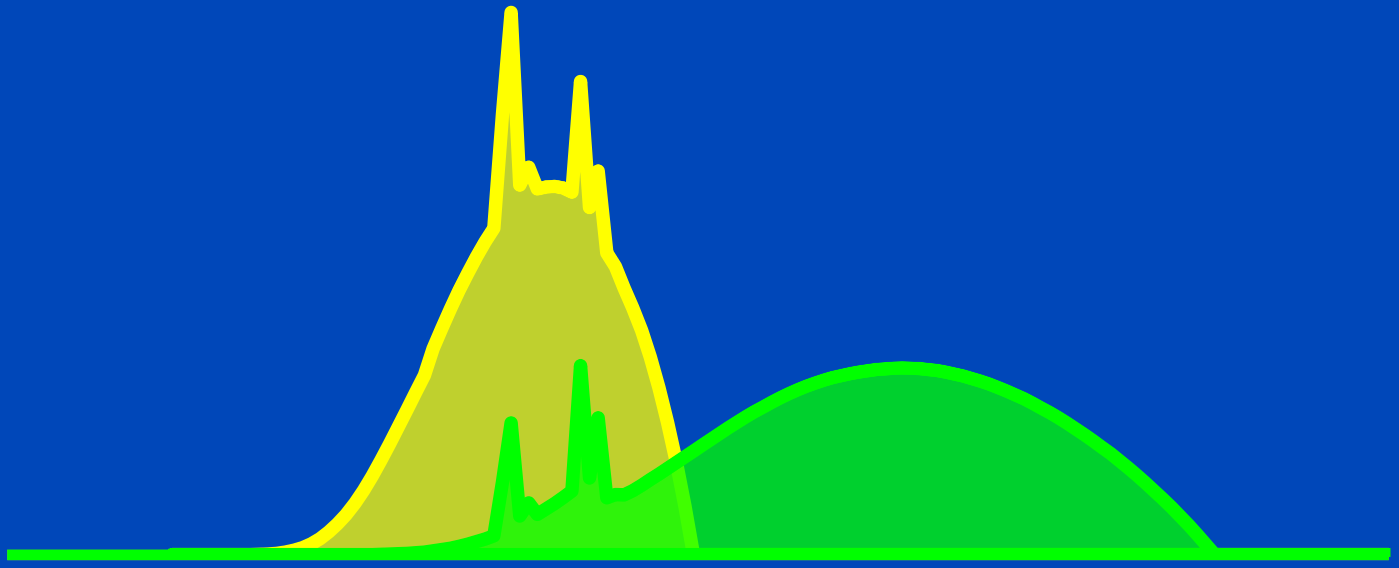


Used in
- GE's fast tube voltage switching CT

Spectra as seen after having passed a 32 cm water layer.

80 kV / 140 kV $Sn_{0.4\ mm}$

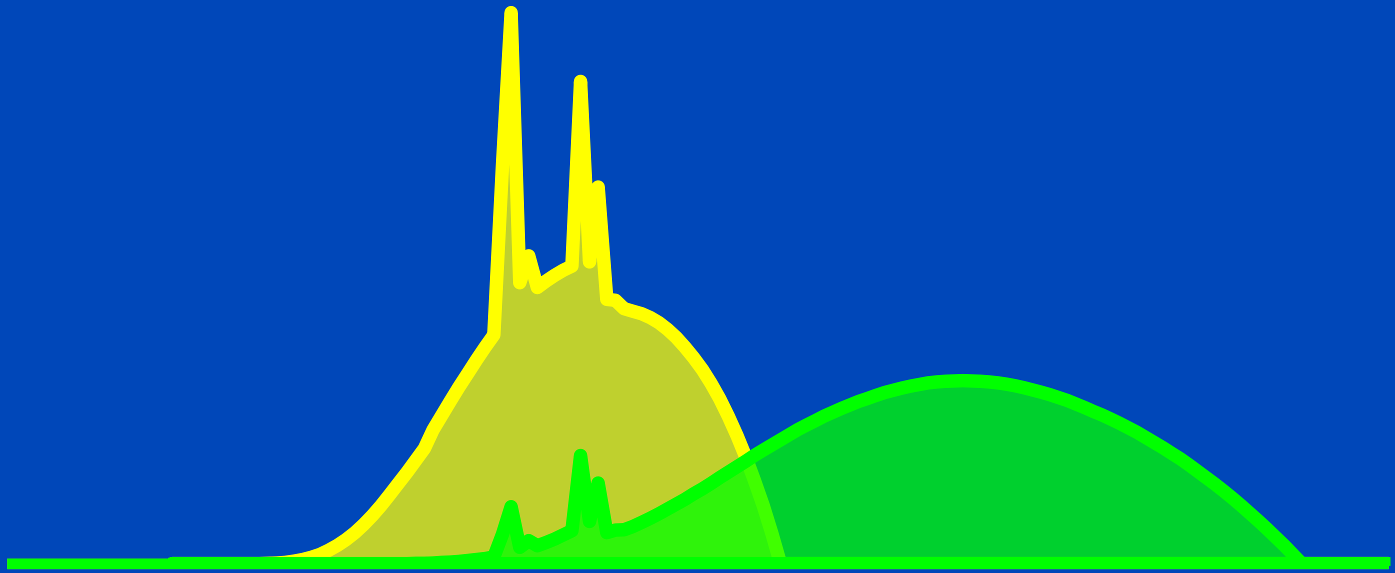
Used in
- Siemens‘ 2nd generation DSCT



Spectra as seen after having passed a 32 cm water layer.

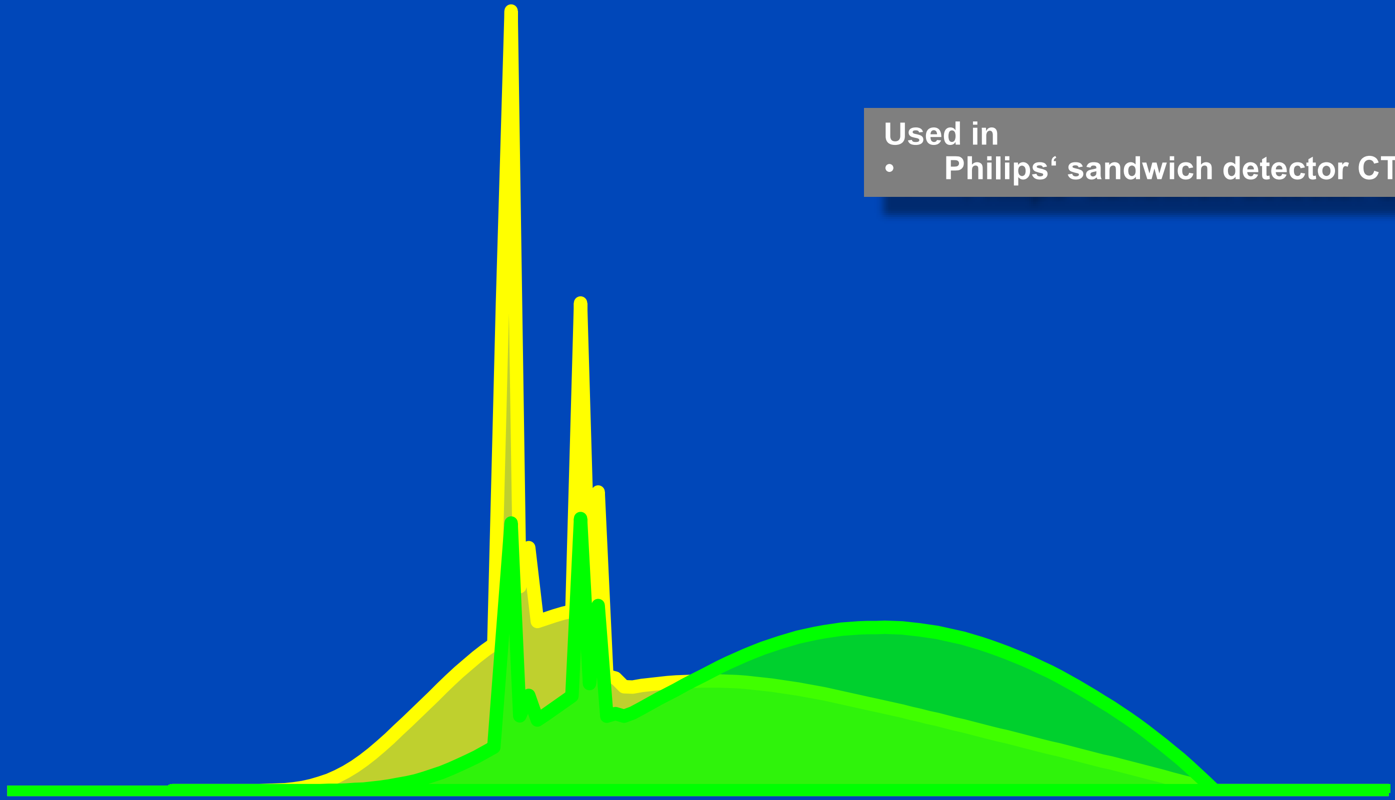
90 kV / 150 kV $Sn_{0.6\ mm}$

Used in
- Siemens‘ 3rd generation DSCT



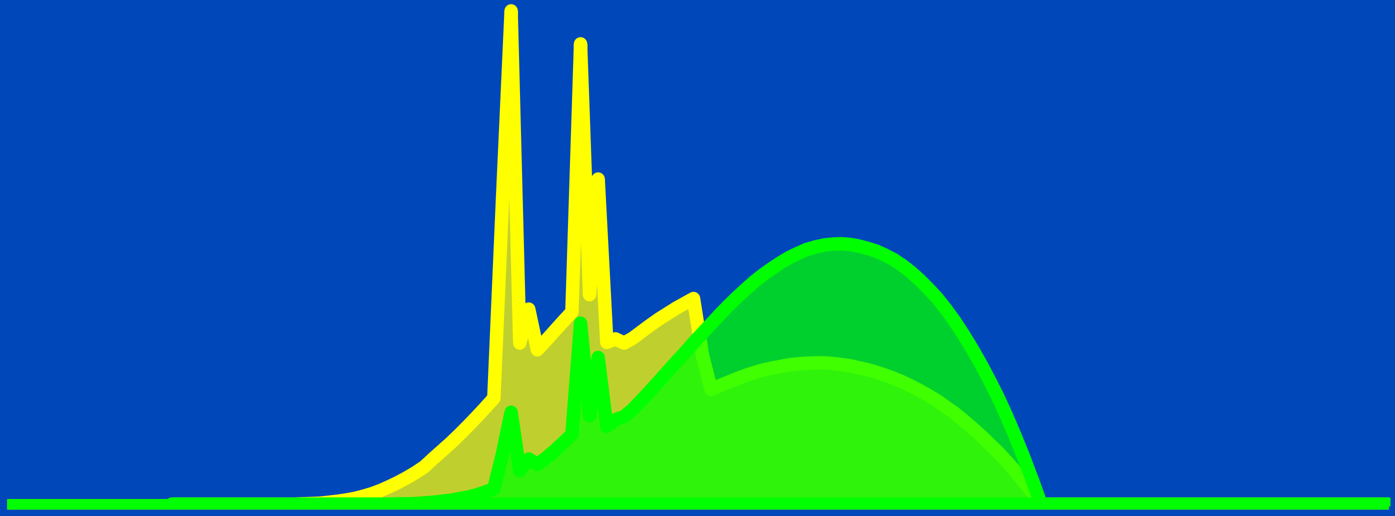
Spectra as seen after having passed a 32 cm water layer.

140 kV YAG / GOS



Used in
- **Philips' sandwich detector CT**

Split filter 120 kV (Au+Sn)



Used in
- Siemens' split filter DSCT

Spectra as seen after having passed a 32 cm water layer.

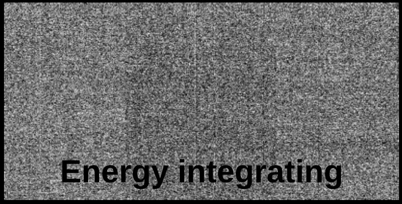
Premium CT Systems 2019/2020

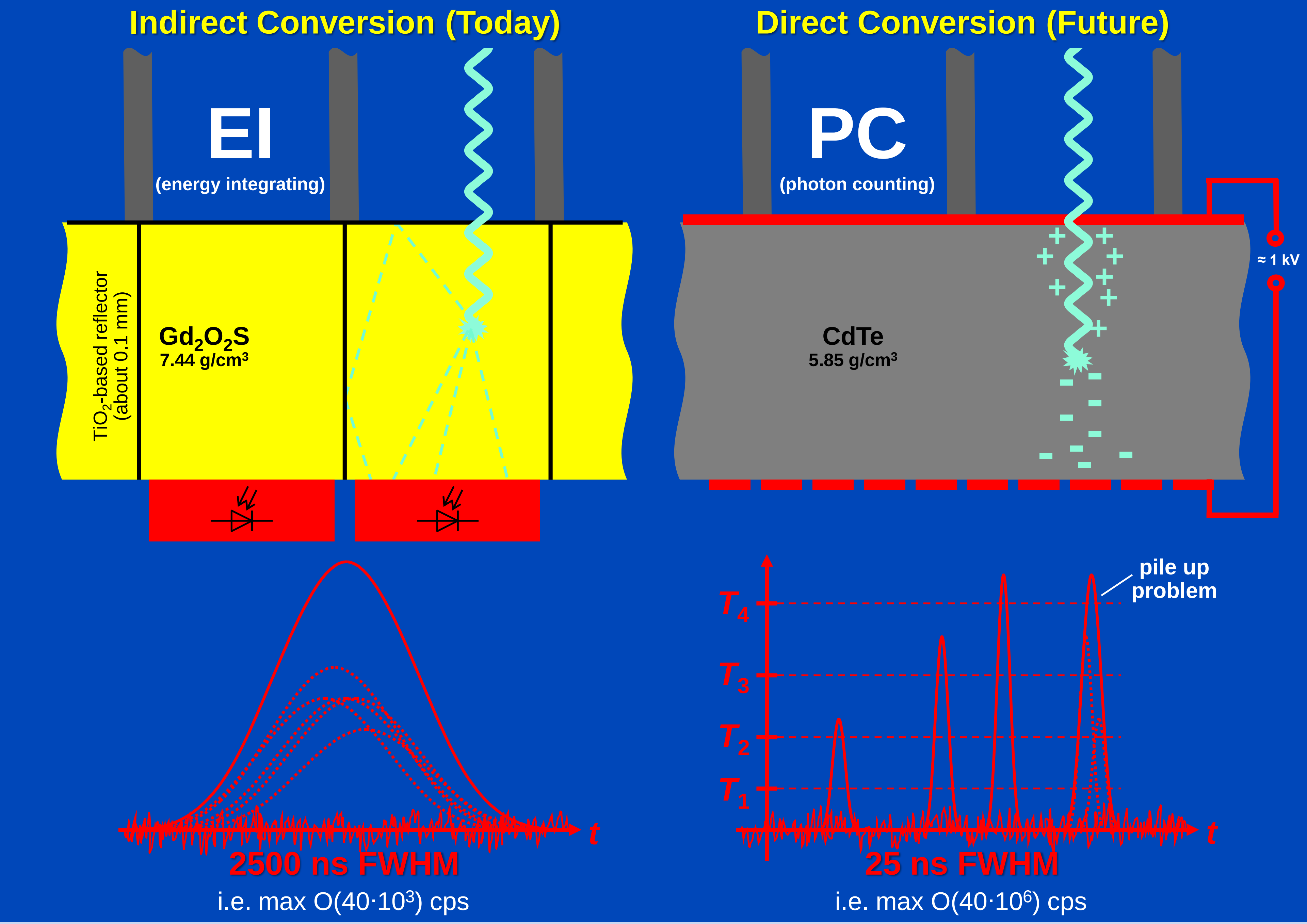
Vendor	CT-System	Configuration	Collim, Cone	Rotation, FOM	Max. Power, Anode Angle	Max. mA @ low kV, patient-specific filters	Matrix	DECT
Canon	Aquilion ONE Genesis	320 × 0.5 mm PUREViSION	160 mm, 15°	0.275 s, 50 cm	100 kW, 10° MegaCool Vi	600 mA @ 80 kV, none	512	2 scans
Canon	Aquilion Precision	160 × 0.25 mm PUREViSION	40 mm, 3.9°	0.35 s, 50 cm	72 kW, 7° MegaCool	600 mA @ 80 kV, none	512, 1024, 2048	2 scans
GE	Revolution Apex	256 × 0.625 mm GemStone Clarity	160 mm, 15°	0.28 s, 50 cm	108 kW, 10° Quantix 160	1300 mA @ 70+80 kV, none	512	fast TVS or 2 scans
GE	CardioGraphe	192 × 0.73 mm (focused FOM)	140 mm, 17°	0.24 s, 25 cm	72 kW, 13° Dual MCS-2093	600 mA @ 80 kV, none	512	2 scans
Philips	Brilliance iCT	2 · 128 × 0.625 mm NanoPanel 3D	80 mm, 7.7°	0.27 s, 50 cm	120 kW, 8° iMRC	925 mA @ 80 kV, none	512, 768, 1024	2 scans
Philips	IQon	2 · 64 × 0.625 mm NanoPanel Prism	40 mm, 3.9°	0.27 s, 50 cm	120 kW, 8° iMRC	925 mA @ 80 kV, none	512, 768, 1024	sandwich
Siemens	Somatom X.cite	2 · 64 × 0.6 mm Stellar	38.4 mm, 3.7°	0.3 s, 50 cm	105 kW, 8° Vectron	1200 mA @ 70+80+90 kV, {0, 0.4, 0.7} mm Sn	512, 768, 1024	split filter or 2 scans
Siemens	Somatom Force	2 · 2 · 96 × 0.6 mm Stellar	57.6 mm, 5.5°	0.25 s, 50/36 cm	2 · 120 kW, 8° Vectron	2 · 1300 mA @ 70+80+90 kV, {0, 0.6} mm Sn	512, 768, 1024	DSCT
Siemens experimental	Somatom CounT	32×0.5/24×0.25 mm (photon counting)	16 mm, 1.5°	0.5 s, 50/28 cm	77 kW, 7° Straton MX P	500 mA @ 70 kV {0, 0.4} mm Sn	512, 768, 1024, 2048	4 bin PC

Photon Counting

Photon counting (here: Dectris detector), C/W=1 cnts/2 cnts

X-rays are off!





Requirements for CT: up to 10^9 x-ray photon counts per second per mm^2.
Hence, photon counting only achievable for direct converters.

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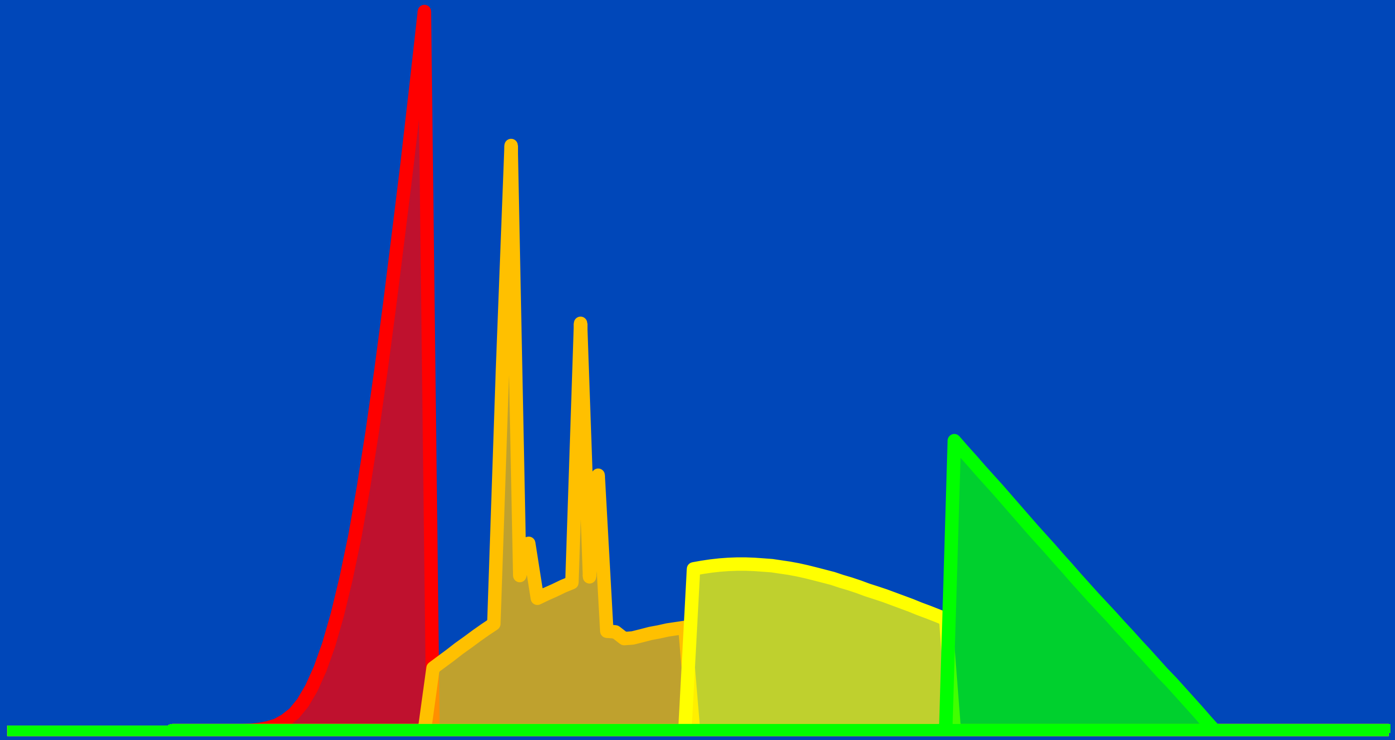
Energy-Selective Detectors: Improved Spectroscopy, Reduced Dose?

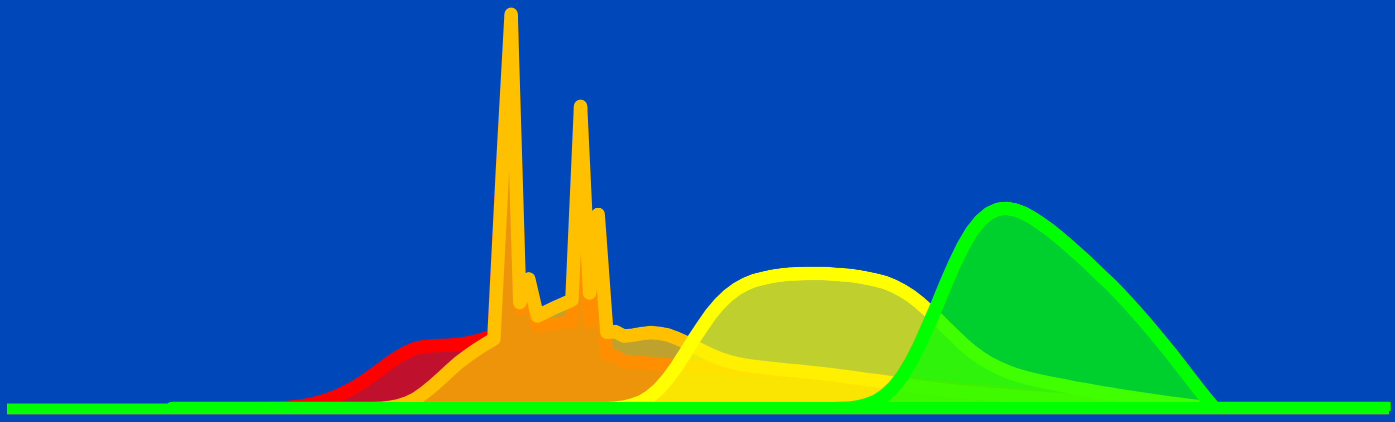
Ideally, bin spectra do not overlap, …



Spectra as seen after having passed a 32 cm water layer.

Energy-Selective Detectors: Improved Spectroscopy, Reduced Dose?

… realistically, however they do!

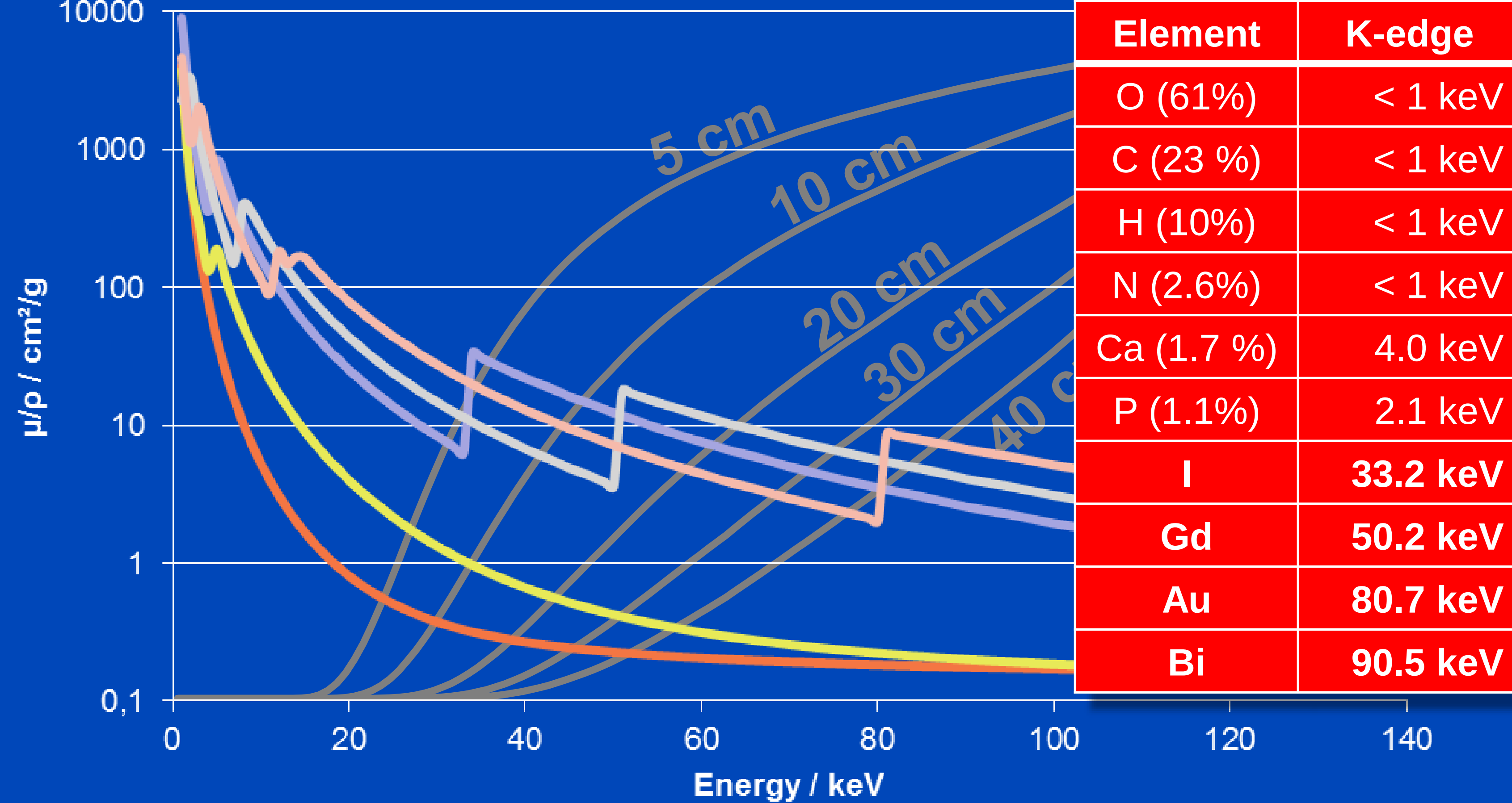


Spectra as seen after having passed a 32 cm water layer.

K-Edges: More than Dual Energy CT?

$$\mu(\boldsymbol{r}, E) = f_1(\boldsymbol{r})\psi_1(E) + f_2(\boldsymbol{r})\psi_2(E) + f_3(\boldsymbol{r})\psi_3(E) + \ldots$$

Apart from special applications, e.g. Iodine k-edge imaging of the breast



Element	K-edge
O (61%)	< 1 keV
C (23 %)	< 1 keV
H (10%)	< 1 keV
N (2.6%)	< 1 keV
Ca (1.7 %)	4.0 keV
P (1.1%)	2.1 keV
I	**33.2 keV**
Gd	**50.2 keV**
Au	**80.7 keV**
Bi	**90.5 keV**

Gray curves: 120 kV water transmission on a non-logarithmic ordinate individually normalized to 1 at 140 keV.

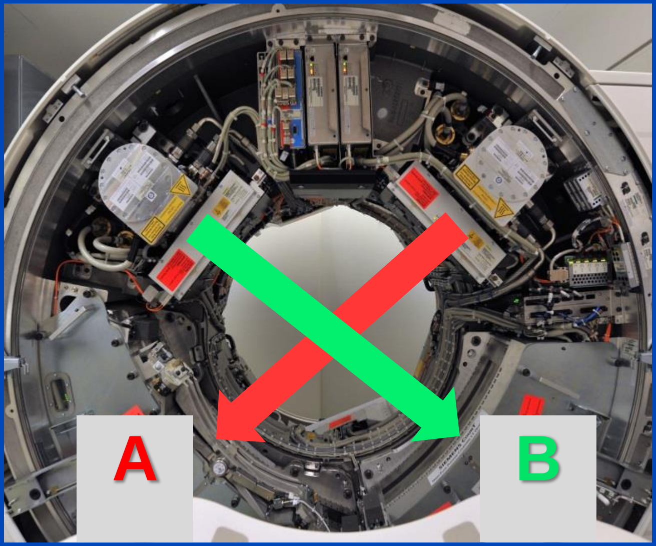

SIEMENS
SOMATOM CounT
@ dkfz.

Siemens CounT CT System

Gantry from a clinical dual source scanner

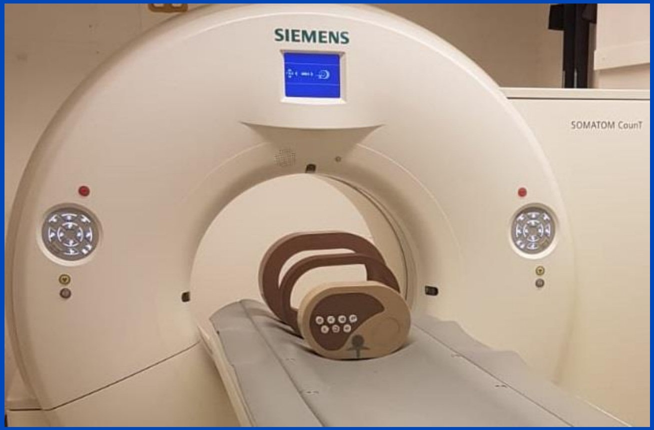
A: conventional CT detector (50.0 cm FOV)

B: Photon counting detector (27.5 cm FOV)



Readout Modes of the CounT

PC-UHR Mode	PC-Macro Mode	EI detector
0.25 mm pixel size	0.50 mm pixel size	0.60 mm pixel size

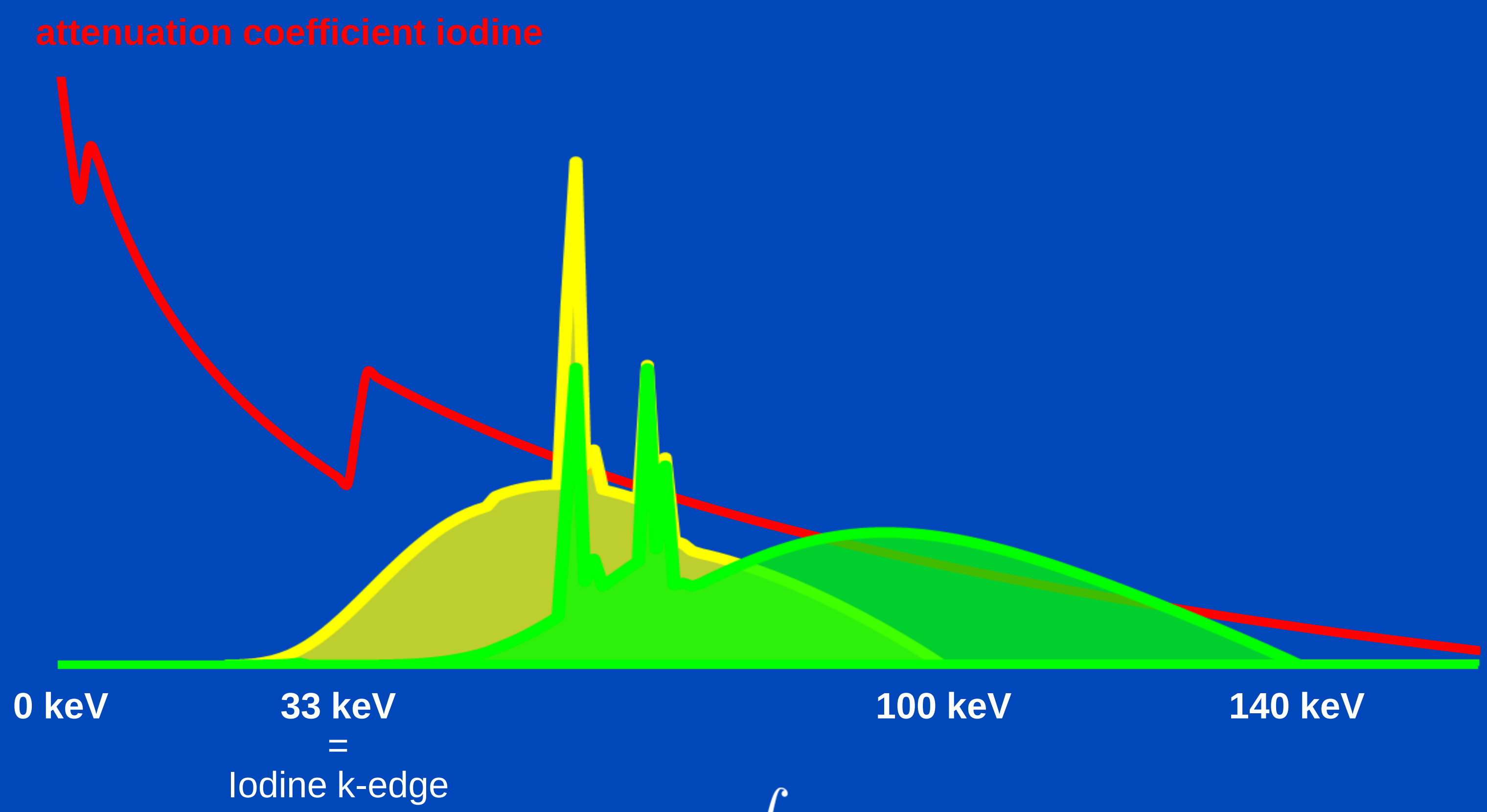


Experimental CT, not commercially available.

Advantages of Photon Counting CT

- No reflective gaps between detector pixels
  - Higher geometrical efficiency
  - Less dose
- No electronic noise
  - Less dose for infants
  - Less noise for obese patients
- Counting
  - Swank factor = 1 = maximal
  - “Iodine effect“ due to higher weights on low energies
- Energy bin weighting
  - Lower dose/noise
  - Improved iodine CNR
- Smaller pixels (to avoid pileup)
  - Higher spatial resolution
  - “Small pixel effect” i.e. lower dose/noise at conventional resolution
- Spectral information on demand
  - Dual Energy CT (DECT)
  - Multi Energy CT (MECT)

Energy Integrating
(Detected Spectra at 100 kV and 140 kV)



$$\mathrm{Signal}_{\mathrm{EI}} = \int dE\, E\; N(E)$$

Spectra as seen after having passed a 32 cm water layer.

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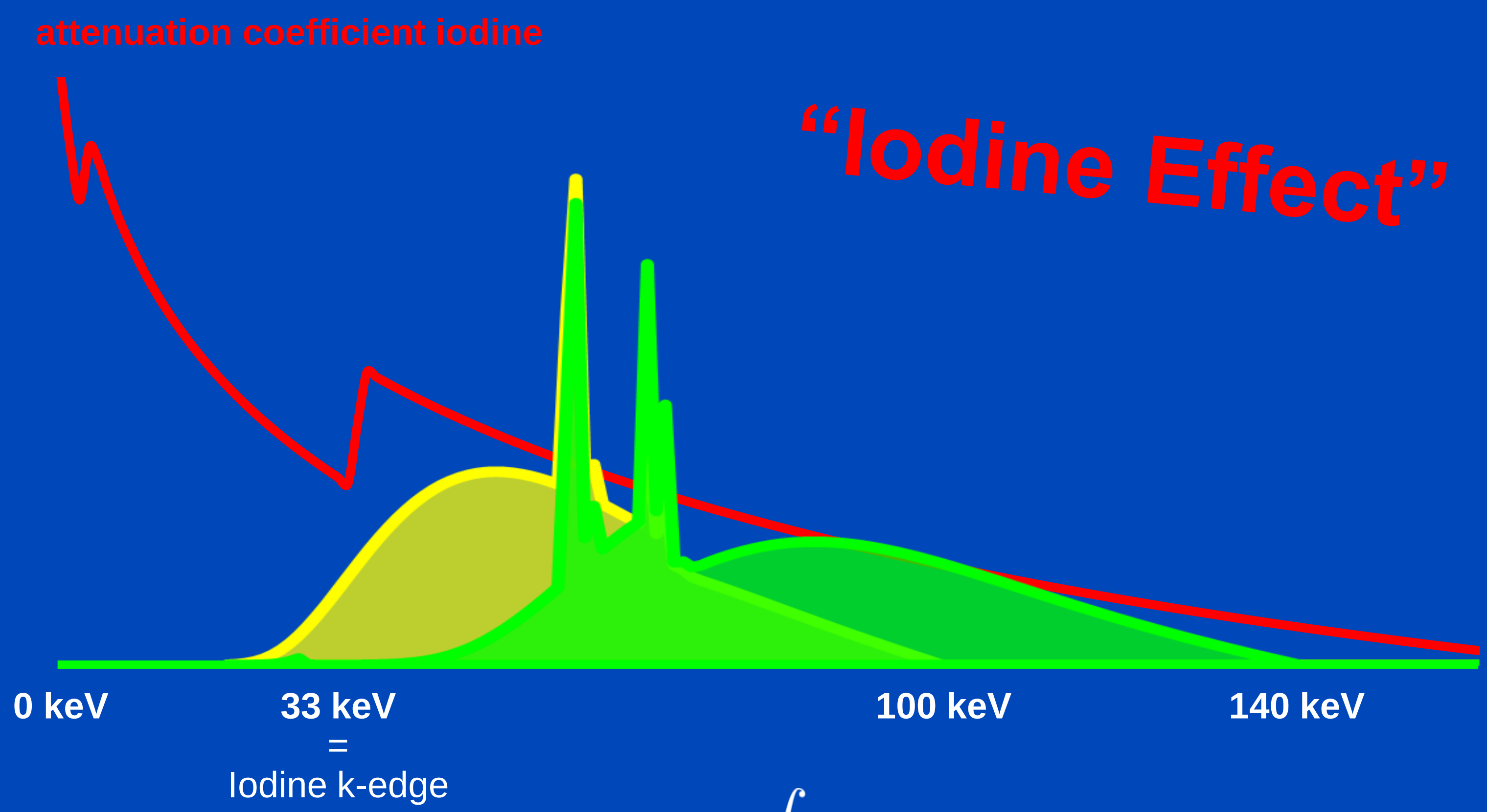
Photon Counting
(Detected Spectra at 100 kV and 140 kV)



$$\mathrm{Signal}_{\mathrm{PC}} = \int dE\, 1\;\; N(E)$$

Spectra as seen after having passed a 32 cm water layer.

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Photon Counting used to Maximize CNR

- With PC energy bin sinograms can be weighted individually, i.e. by a weighted summation
- To optimize the CNR the optimal bin weighting factor w_b is given by (weighting after log):

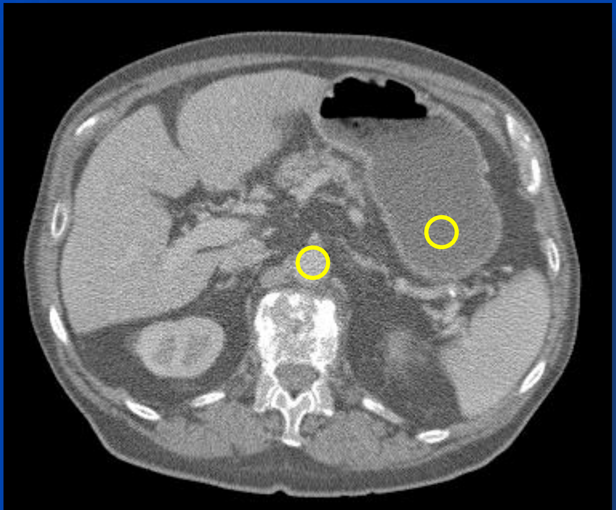
$$w_b \propto \frac{C_b}{V_b}$$

- The resulting CNR is

$$\mathrm{CNR}^2 = \frac{\left(\sum_b w_b C_b\right)^2}{\sum_b w_b^2 V_b}$$

- At the optimum this evaluates to

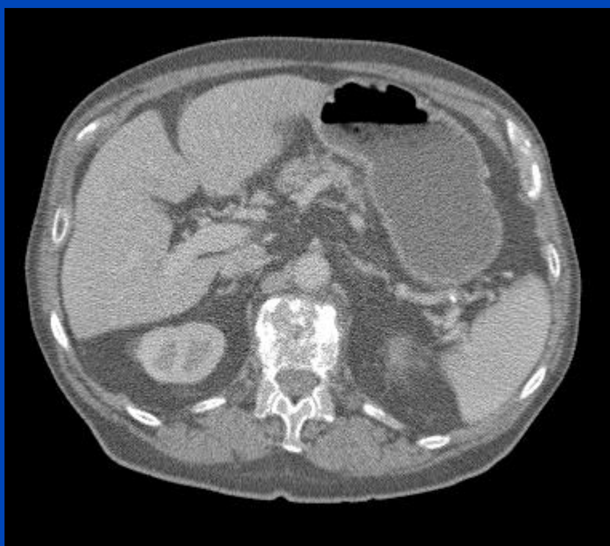
$$\mathrm{CNR}^2 = \sum_{b=1}^{B} \mathrm{CNR}_b^2$$



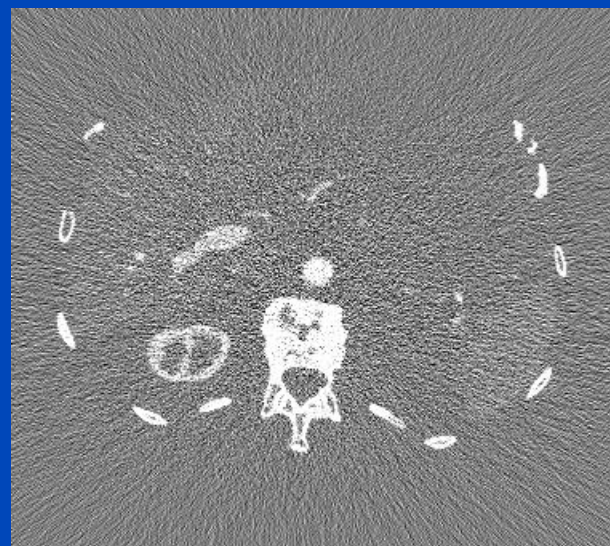
The two ROIs are used to measure the CNR.

Energy Integrating vs. Photon Counting
with 4 bins from 20 to 140 keV

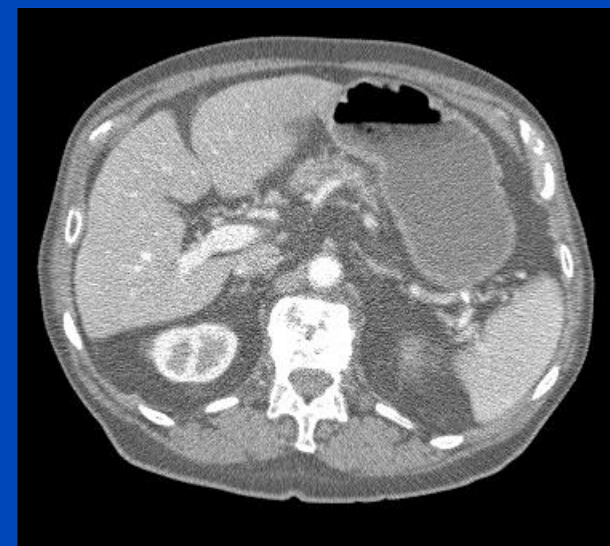
Energy Integrating



PC minus EI

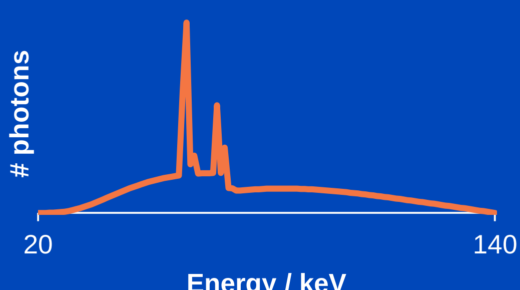


Photon Counting

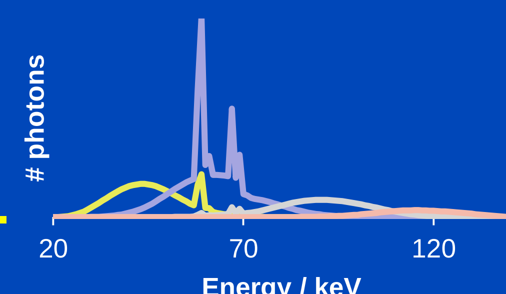


CNR = 2.11

CNR = 4.19



99% CNR improvement or 75% dose reduction achievable due to improved Swank factor and optimized energy weighting.



Images: *C* = 0 HU, *W* = 700 HU, difference image: *C* = 0 HU, *W* = 350 HU, bins start at 20 keV

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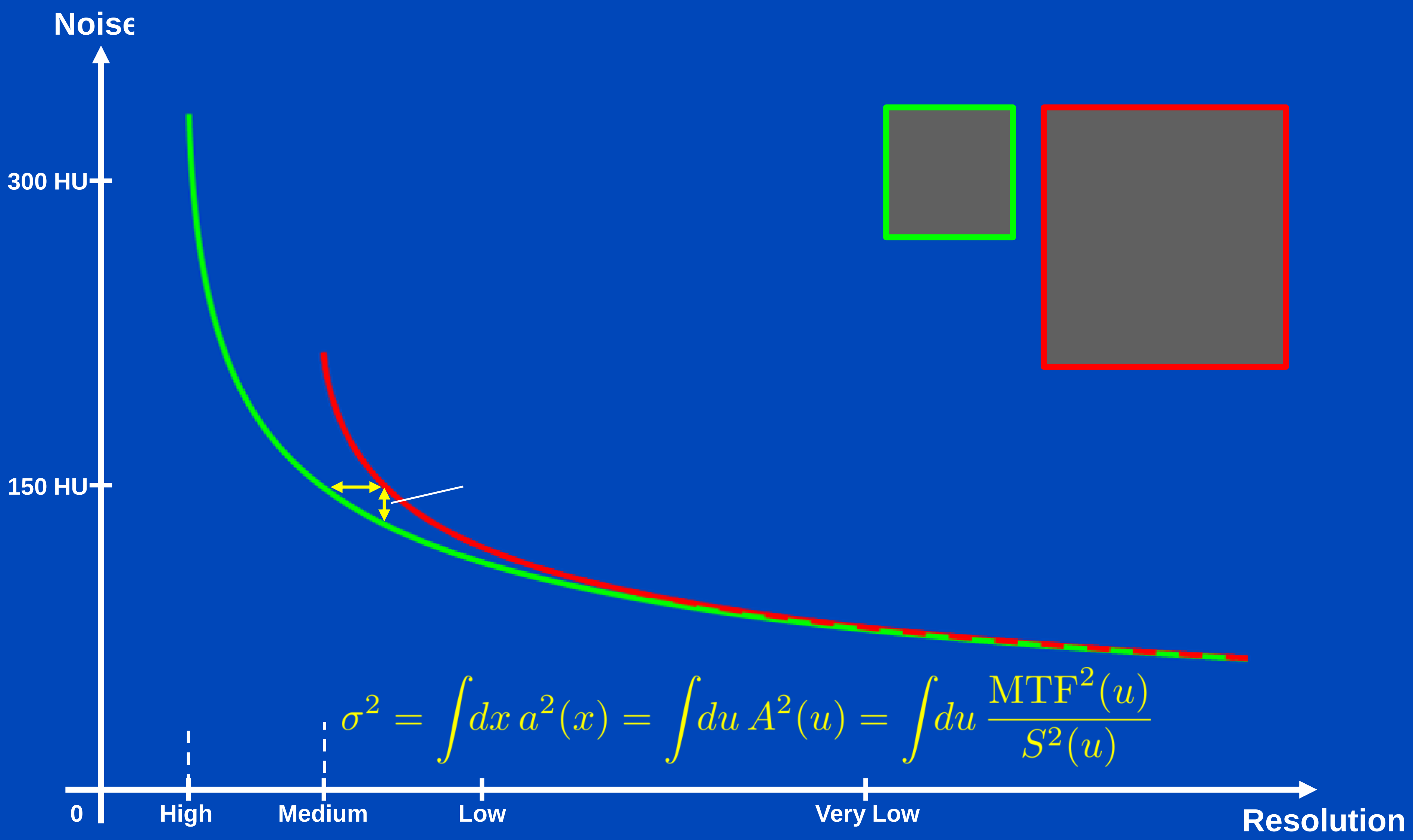
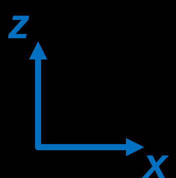
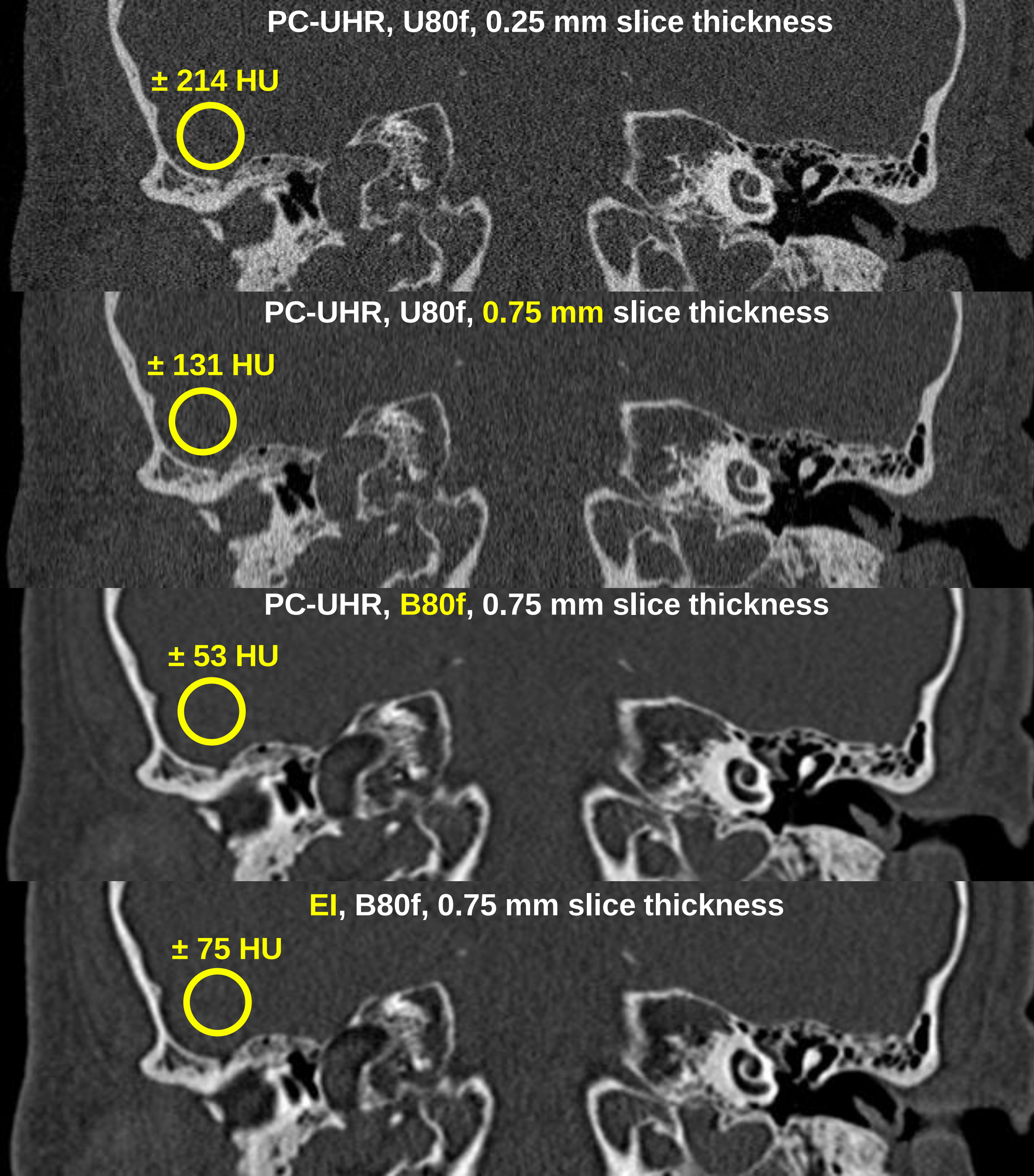
The "Small Pixel Effect"



$$\sigma^2 = \int dx\, a^2(x) = \int du\, A^2(u) = \int du\, \frac{\mathrm{MTF}^2(u)}{S^2(u)}$$

All images reconstructed with 1024^2 matrix and 0.15 mm slice increment.
***C* = 1000 HU**
***W* = 3500 HU**





10% MTF: 19.1 lp/cm
10% MTF:17.2 lp/cm
xy FWHM: 0.48 mm
z FWHM: 0.40 mm
$CTDI_{vol}$: 16.0 mGy

10% MTF: 19.1 lp/cm
10% MTF:17.2 lp/cm
xy FWHM: 0.48 mm
z FWHM: 0.67 mm
$CTDI_{vol}$: 16.0 mGy

10% MTF: 9.3 lp/cm
10% MTF:10.5 lp/cm
xy FWHM: 0.71 mm
z FWHM: 0.67 mm
$CTDI_{vol}$: 16.0 mGy

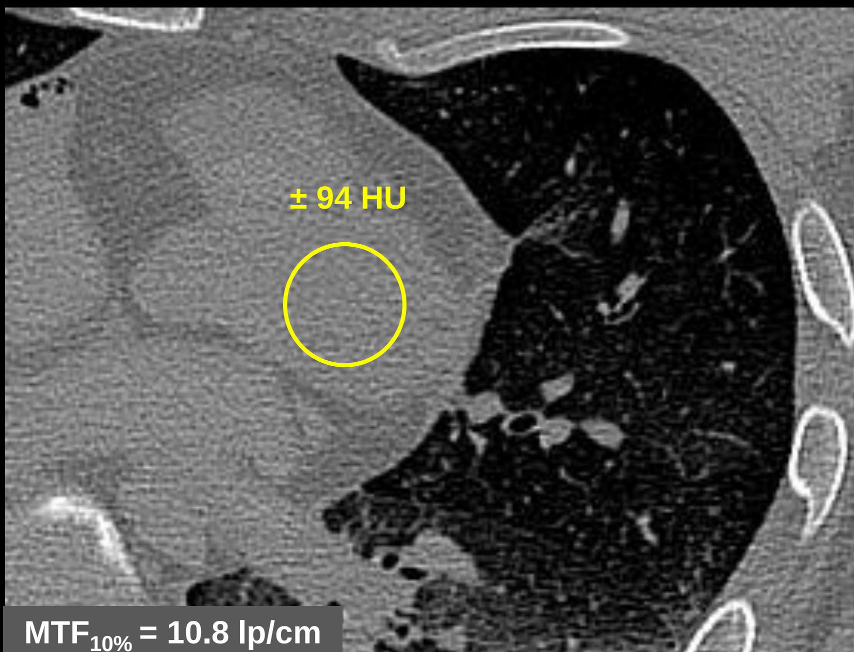
10% MTF: 9.3 lp/cm
10% MTF:10.5 lp/cm
xy FWHM: 0.71 mm
z FWHM: 0.67 mm
$CTDI_{vol}$: 16.0 mGy

Data courtesy of the Institute of Forensic Medicine of the University of Heidelberg and of the Division of Radiology of the German Cancer Research Center (DKFZ)

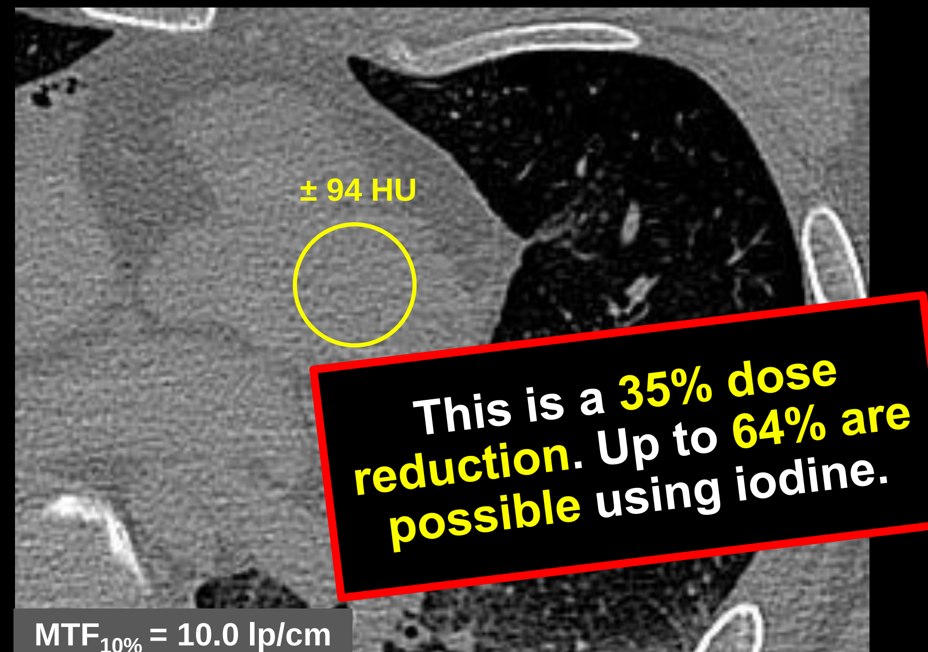
dkfz.

L. Klein, C. Amato, S. Heinze, M. Uhrig, H.-P. Schlemmer, M. Kachelrieß, and S. Sawall. **Effects of Detector Sampling on Noise Reduction in a Clinical Photon Counting Whole-Body CT**. Investigative Radiology, vol. 55(2):111-119, February 2020.

Energy Integrating Detector (B70f)



Photon Counting Detector (B70f)



Acquisition with EI:

- **Tube voltage of 120 kV**
- **Tube current of 300 mAs**
- **Resulting dose of $CTDI_{vol\ 32\ cm}$ = 22.6 mGy**

Acquisition with UHR:

- **Tube voltage of 120 kV**
- **Tube current of 180 mAs**
- **Resulting dose of $CTDI_{vol\ 32\ cm}$ = 14.6 mGy**

C = 50 HU, W = 1500 HU

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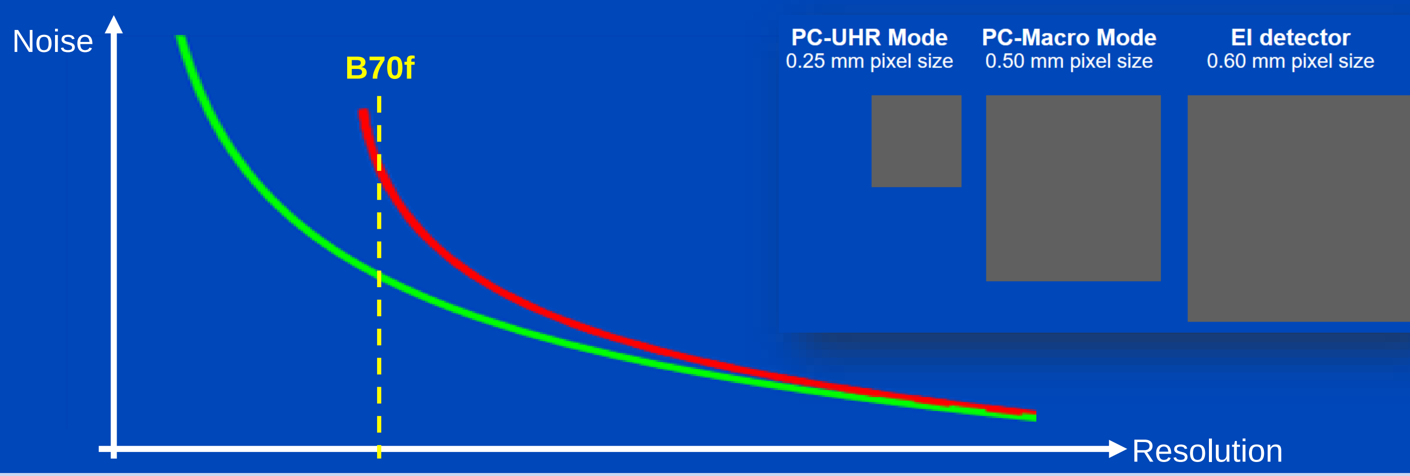
X-Ray Dose Reduction of B70f

PC vs. PC ("pixel effect only")

UHR vs. Macro	80 kV	100 kV	120 kV	140 kV
S	**23%** ± 12%	**34%** ± 10%	**35%** ± 11%	**25%** ± 10%
M	**32%** ± 10%	**32%** ± 8%	**35%** ± 8%	**34%** ± 9%
L	**35%** ± 10%	**29%** ± 15%	**27%** ± 9%	**31%** ± 11%

PC vs. EI ("pixel effect" and "iodine effect")

UHR vs. EI	80 kV	100 kV	120 kV	140 kV
S	**33%** ± 9%	**52%** ± 5%	**57%** ± 7%	**57%** ± 6%
M	**41%** ± 8%	**47%** ± 7%	**60%** ± 6%	**62%** ± 4%
L	**48%** ± 8%	**43%** ± 10%	**54%** ± 6%	**63%** ± 5%



Summary

- **Dual energy CT**
  - Several realizations of dual energy CT available
  - DECT does not necessarily increase or decrease dose although two simultaneous acquisitions are performed
  - Dose in DECT is partitioned into the low and the high kV scan
- **Photon-counting multi energy CT**
  - Intrinisically performs energy-selective acquisition
  - Separation of more materials difficult – would require development of novel contrast agents
  - Significantly higher spatial resolution
  - Significantly higher dose efficiency due to basic physic principles

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (marc.kachelriess@dkfz.de).

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.